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MASTER IN COMPUTER SCIENCE

AODV enhanced by Smart Antennas

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Award date:
2005

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University of Namur
Computer Science Institute
Academic year 2004-2005

AODV enhanced by Smart Antennas

Alain Solheid

Final thesis presented with the objective of obtaining the grade of a
"Master in computer science"

Abstract

In the recent years, ad-hoc network technologies have received much attention from the research community. Therefore, the evolution of these technologies is more rapid, but also results in more complex devices and mechanisms.

Furthermore, smart antenna systems have recently become more attractive for utilization in ad-hoc networks, mainly because their cost has been decreasing steadily.

This document treats both subjects, the ad-hoc networks and smart antenna systems, in a detailed manner and especially focuses on their interaction. It will mainly address the question whether smart antennas can increase the global performance of ad-hoc networks.

Keywords: wireless ad-hoc network, smart antenna, CSMA/CA, AODV, adaptive array antenna

Résumé

Dans les années récentes, les technologies des réseaux ad-hoc ont reçu beaucoup plus d'attention de la communauté de recherche. Grâce à ça, l'évolution de ces technologies est plus rapide, mais résulte aussi en des dispositifs et mécanismes plus complexes.

Par ailleurs, les systèmes d'antennes intelligentes sont récemment devenus plus attractifs pour l'utilisation dans des réseaux ad-hoc et grâce à la baisse des coûts.

Ce document traite les deux sujets, à savoir les réseaux ad-hoc et les systèmes d'antennes intelligentes, de manière détaillée et en insistant sur leurs interactions. Il va principalement traiter la question de savoir si les antennes intelligentes peuvent augmenter la performance globale des réseaux ad-hoc.

Mots clés : réseaux ad-hoc, antenne intelligents, CSMA/CA, AODV, arrangement d'antenne adaptive

Glossary

AAA	Adaptive Array Antenna
ACK	Acknowledgement
AIFS	Arbitration Interframe Space
AM	Amplitude Modulation
AODV	Ad-hoc On-demand Distance Vector
AP	Access Point
ARQ	Automatic Repeat Request
BER	Bit Error Rate
BPSK	Binary Phase Shift Keying
BSS	Basic Service Set
CDMA	Code Division Multiple Access
CF	Coordination Function
CRC	Cycle Redundancy Code
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
CSMA/CD	Carrier Sense Multiple Access with Collision Detection
CTS	Clear-To-Send
CW	Contention Window
DCF	Distributed Coordination Function
DIFS	Distributed Interframe Space
DSN	Destination Sequence Number
DSP	Digital Signal Processing
EIFS	Extended Interframe Space
EMF	Electromotive Force
ESS	Extended Service Set
FDD	Frequency Division Duplex
FM	Frequency Modulation
HSLS	Hazy Sighted Link State
IBSS	Independent Basic Service Set
IEEE	Institute of Electrical and Electronics Engineers
IEEE 802.3	Ethernet
IEEE 802.11	Wireless network (e.g. WiFi)
IFS	Interframe Space
IP	Internet Protocol
LLC	Logical Link Control
LMS	Least Mean Square
MAC	Medium Access Control
NAV	Network Allocation Vector
OSI	Open Systems Interconnection
OSN	Originator Sequence Number
PCF	Point Coordination Function
PHY	Physical Layer
PIFS	Point coordination function Interframe Space
PLCP	Physical Layer Convergence Protocol
PMD	Physical Medium Dependant
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RERR	Route Error
RF	Radio Frequency
RREP	Route Reply
RREQ	Route Request
RTS	Request-To-Send
SDMA	Space-Division Multiple Access
SIFS	Short Interframe Space
SNR	Signal-to-Noise Ratio
SWR	Standing Wave Ratio
TDD	Time Division Duplex
TDMA	Time-Division Multiple-Access
UDAAN	Utilizing Directional Antennas for Ad-hoc Networks
UDP	User Datagram Protocol
WLAN	Wireless Local Area Network

Acknowledgments

I would like to thank *Dr. Yukihiro Kamiya*, Associate Professor, and *Dr. Yasuo Suzuki*, Professor, at Tokyo University of Agriculture and Technology for their support and encouragements. Also I appreciate helpful discussions and friendship of my collegues of the Kamiya laboratory.

I would like to thank, *Dr. Laurent Schumacher*, Assistant Professor, University of Namur (FUNDP), Belgium, for his administrable guidance.

This project was partly supported by *Honda Foundation Belgium*.

Einen besonderen Dank an meine Eltern, ohne die dieses Praktikum nicht möglich gewesen wäre.

Contents

List of Figures

Chapter 1

Introduction

In the recent years, ad-hoc networking has driven much attention from the wireless research community and industry. Ad-hoc networks form when stations with similar architecture come into close proximity and start to communicate spontaneously. Therefore, ad-hoc networks must create their own infrastructure in a dynamic and distributed way, without any centralized coordination. Ad-hoc networks are often used for military systems, disaster area networks and conference networks. As wireless communication is more and more embedded into different devices, the role of ad-hoc networks is expected to expand. This larger use of ad-hoc networks also anticipates the development and enhancement of ad-hoc routing protocols.

The ad-hoc on-demand distance vector (AODV) is one of these routing protocols. It is created for mobile ad-hoc networks with tens to thousands of participating mobile nodes. AODV can master low, moderate, and relatively high mobility rates, as well as a variety of data traffic levels. AODV is meant for networks where the nodes can all trust each other, either by the use of preconfigured keys, or because it is known that there are no vicious intruder nodes in the network. AODV has been designed to minimize the propagation of control traffic and prevent overhead on data traffic, in order to enhance both, scalability and performance of ad-hoc networks [12].

Also in recent years, adaptive array antennas (AAAs) have been increasingly tested for use in mobile applications. However, most of the commercial wireless communication are omni directional. Multiple antenna systems have only very slowly found their way into commercial applications due to their cost and rather poor support from legacy air interfaces. But in the past few years, the cost for multiple antenna systems has been decreasing steadily and it seems that AAAs will eventually find their way into future ad-hoc networks. The potential benefits of using such AAAs in ad-hoc networks include increased network capacity, enhanced service quality and improved low power mode operation. Thus, the antenna will surely bring many advantages to ad-hoc network operations.

The general motivation for the project will now be shortly described.

1.1 Ad-hoc Networks and Smart Antennas

It is widely known that ad-hoc networks form when nodes come within range and communicate in the absence of any fixed infrastructure [1]. The basic notion of ad-hoc packet communication already exists for many years and has found its way into standards like the IEEE 802.11. In IEEE 802.11, stations can operate in IBSS (independent basic service set) mode, which provides communication without fixed infrastructure. The usual ad-hoc mode of operation involves direct communications between the source and destination nodes when they are both within range.

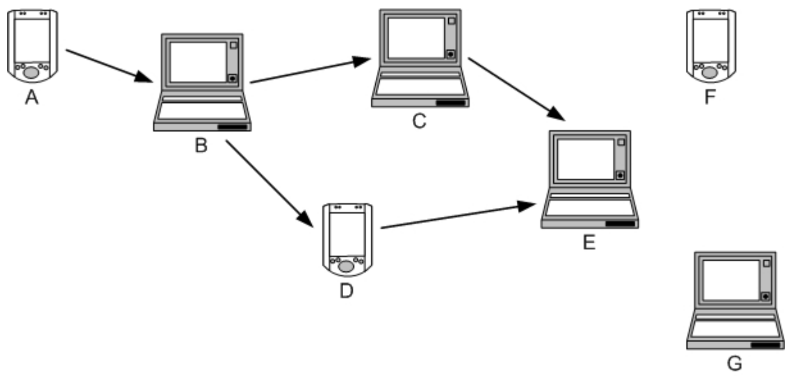


Figure 1.1: Ad-hoc multihop communication

Unfortunately, the case where the wireless coverage areas of the source and destination nodes do not coincide is very likely. The nodes must thus use multihop communication where all nodes have to act as a router. Therefore, ad-hoc network routing protocols must be developed to dynamically establish routes by chaining together a sequence of neighboring hosts from the source to the destination. An example is shown in Figure 1.1. In this network, node A cannot communicate directly with node E since they are out of range. Using multihop communications however, node A can reach node E via wireless relaying through neighboring nodes such as the paths shown as A-B-C-E and A-B-D-E. This type of multihop communication obviously implies a routing function and much of the recent work on ad-hoc networks deals with the design of routing algorithms that can operate in a more stable way in presence of time varying topologies caused by the mobility of nodes. Thus, many strongly differing routing protocols have been proposed in the recent years.

One of those routing protocols is the *Ad-hoc On demand Distance Vector (AODV)* protocol. In this protocol, each mobile station operates as a specialized router and routes are obtained whenever needed, i. e. on demand, with little or no reliance on periodic advertisements [12]. The routing algorithm is quite suitable for a dynamic self-starting network as required by users wishing to use ad-hoc networks. AODV provides loop-free routes even while repairing broken links. Because the protocol does not require global periodic routing advertisements, the demand on the overall bandwidth available to the mobile nodes is substantially less than in protocols that do necessitate such advertisements. Nevertheless, it is still possible to maintain most of the advantages of basic distance vector routing mechanisms. The algorithm scales to large populations of mobile nodes needing to form ad-hoc networks.

Furthermore, a media access protocol (MAC) is required to efficiently activate links in an ad-hoc network. In the IEEE 802.11 standard the MAC protocol used is the *Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA)* protocol. Unlike the Carrier Sense Multiple Access with Collision Detection (CSMA/CD) which deals with transmissions after a collision has occurred, CSMA/CA acts to prevent collisions before they happen. All stations apply this standard mechanism to avoid collision of wireless messages. The sender cannot detect if a collision has occurred, so it attempts to avoid collisions by waiting for the wireless medium to be clear for the amount of time it takes for a packet to propagate through the entire medium, i.e., for a packet to be sent from the station farthest away.

The communication between the MAC layer protocol (CSMA/CA) and the AODV routing protocol have already been tested by simply applying the AODV protocol into an IEEE 802.11 wireless local area network and thus, have been proved to be very effective in its cooperation.

On the other side, the principles of MAC protocol design using omni directional antenna transmission have been studied for many years and are now well understood. This leads us to the *Adaptive Array Antennas (AAAs)*. Such a system tracks the mobile user continuously by steering the main beam, also called main lobe, towards him/her and at the same time forming nulls in the directions of interferers. AAAs incorporate arrays of antenna elements. Typically, the received signal from each of the spatially distributed antenna elements is multiplied by a weight. The weights are complex in nature and adjust the amplitude and phase. These signals are combined to yield the array output. These complex weights are computed by a complicated adaptive algorithm, which is pre-programmed into the digital signal-processing unit that manages the signal radiated by the base station.

The addition of AAAs provides stations with directional gain during both transmission and reception in an ad-hoc network. This directional selectivity has the potential for reducing co-channel interference compared with the omni directional systems, and can result in increased capacity and link performance. This additional gain can also increase the range over which links can be reliably activated. Thus, we can assume that the performance of routing protocols such as the AODV protocol will be improved.

1.2 Topic of the Project

After this brief introduction to the theoretical background of the project, the topic of the work can now be presented easily.

There are two objectives, as follows:

- *Developing Technologies* – The implementation of the different network technologies introduced in this document, namely the wireless ad-hoc network and the adaptive array antenna;
- *Showing the Improvement* – Moreover, it is aimed to show that the adaptive array antenna improves the performance of wireless ad-hoc protocols, such as AODV, thanks to the higher gain of the antenna.

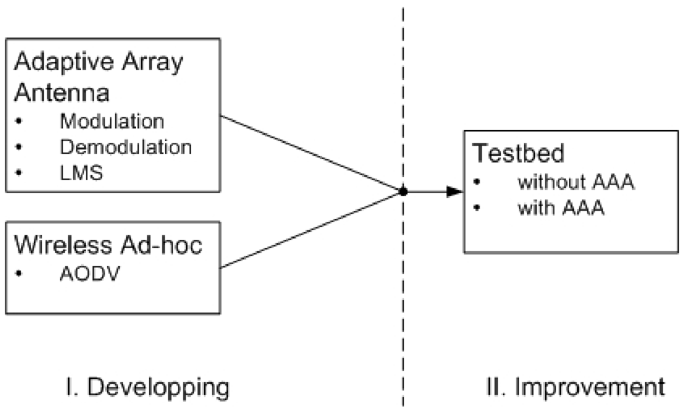


Figure 1.2: Topic of the project

1.2.1 Developing Technologies

The basic technologies that are used within this project are the adaptive array antenna (AAA) and the wireless ad-hoc environment. These are two well-known and widely used technologies in networking today.

To simulate the AAA, it would be necessary to implement the general signal treatment, which includes the modulation and demodulation of signals, as well as an adaptive filter algorithm, namely, within this project, the *Least Mean Square* (LMS) algorithm.

Furthermore, to install a wireless ad-hoc environment, an implementation of the AODV routing protocol should be built.

Once these two technologies established, to advance to the second goal of this project, it will be required to install the AAA into the wireless environment and thus, achieve a complete simulation or testbed of the environment needed.

1.2.2 Showing the Improvement

Today everybody expects, without any further proof or tests, that the AAA effectively improves the efficiency and performance of network routing protocols like AODV.

Thus, the final objective of this project is to prove or at least to test this by simulating the general operation of the testbed system, creating different network configurations and comparing the performance of the AODV protocol with and without the presence of an AAA.

This document contains a detailed introduction to the theoretical background of the underlying project in the chapters 2 to 7. These chapters will be a general introduction to wireless ad-hoc networks, including the CSMA/CA and AODV protocols (chapters 2 - 4) and smart antenna systems, especially the AAA, including the signal treatment and adaptive filtering (chapters 5 - 7). These chapters may appear very detailed, as they introduce already well-known theoretical knowledge, but they are more than necessary to understand the contents of the project. In the following chapter (chapter 8), the project status will be described in detail. This chapter contains all original material written by the author. Finally, a conclusion on the main goals, namely the implementation of the different network technologies – the wireless ad-hoc network and the adaptive array antenna – and the proof that the adaptive array antenna improves the performance of wireless ad-hoc protocols, such as AODV, thanks to the higher gain of the antenna, will be provided.

Chapter 2

Wireless Ad-hoc Networks

The next generation of wireless communication will be in need for rapid deployment of independent mobile users. Some important examples are establishing robust, efficient and dynamic communication for emergency and rescue operations, disaster relief efforts, and military networks. These networks cannot rely on centralized and organized connectivity, but should be seen as applications of wireless ad-hoc networks [5].

A wireless ad-hoc network is an autonomous collection of mobile users that communicate over relatively bandwidth constrained wireless links. Since the nodes are mobile, the network topology may change rapidly and unpredictably over time. The network is decentralized and all network activities including discovering the topology and delivering messages must be executed by the node itself, i. e. routing functionality will be incorporated into mobile nodes.

Applications for wireless ad-hoc networks are very diverse, from small, static networks that are constrained by power sources, to large-scale, mobile, highly dynamic networks. Designing network protocols for these networks is a difficult and complex task. Moreover, wireless ad-hoc networks need efficient distributed algorithms to determine network organization, link scheduling, but also routing. However, determining viable routes and delivering messages in this decentralized environment where the network topology vary with the time is not a well-defined problem. While the shortest path (based on a given routing algorithm with a specified cost function) from source to destination in a static network is usually the optimal route, this does not imply that it is also available for wireless ad-hoc networks. In this environment factors like the variable link quality, propagation path loss, fading, multiuser interference, power wasted, and topological changes, influence the networks' functionality. The wireless ad-hoc network should be able to adaptively change the routing paths to decrease the influence of these effects.

Moreover, in a military environment, the preservation of security, latency, reliability, protection against intentional jamming, and recovery from failure is very important. These networks are also designed to maintain a low probability of intercept and detection. Thus, mobile nodes should only emanate as little power as necessary and transmit as rarely as possible, therefore lowering the probability of detection or interception. Not fulfilling these needs would impair the performance of the network.

Wireless Ad hoc Network Communication

Communication between two hosts in a wireless ad-hoc network is not always direct—it can proceed to multi-hop routing so that every host is also a router. Wireless ad-hoc network hosts can use protocols such as the IEEE 802.11 media-access control standard to communicate via the same frequency, or they can apply Bluetooth or other frequency-hopping technology.

Because power consumption is directly proportional to the distance between hosts, direct single-hop transmissions between two hosts can require significant power, causing interference with other such transmissions. To avoid this routing problem, two hosts can use multi hop transmission to communicate via other hosts in the network.

With IEEE 802.11 technology, avoiding collisions – transmission interferences – is difficult because of the hidden station problem: two hosts which do not communicate directly can transmit messages simultaneously to a common neighbor on the same frequency.

In addition to maintaining an ongoing routing task or facilitating route establishment, mobile networks must also support location management by keeping track of the host's location.

Network Layer Requirements

To manage the network layer effectively a certain number of requirements must be fulfilled. Those requirements of wireless ad-hoc networks include topology control, data communication, and service access. In each of these categories several problems will be encountered.

Topology control problems include discovering neighbors, identifying the position, determining the transmission radius, establishing links to neighbors, scheduling node sleep and active periods, clustering, and maintaining the selected structure.

Data communication problems include the routing-sending a message from a source to a destination node, broadcasting-flooding a message from a source to all other nodes in the network, multi casting-sending a message from a source to a set of desirable destinations, geocasting-sending a message from a source to all nodes inside a geographic region, and location updating-maintaining reasonably accurate information about the location of other nodes.

Finally, service access problems include Internet access, cellular network access, data or service replication upon detection or expectation of network partition, and unique IP addressing in merge or split-network scenarios.

Wireless ad-hoc networks are more precisely defined by the IEEE 802.11 standard introduced in the following. This standard was the guiding line for the project and should therefore be introduced.

2.1 Wireless Communication Standard

The International Standard Organization (ISO) developed a seven-layer model, called Open Systems Interconnection Reference Model (OSI model), for communication systems to solve the problem of incompatible architectures. This model is represented in figure 2.1.

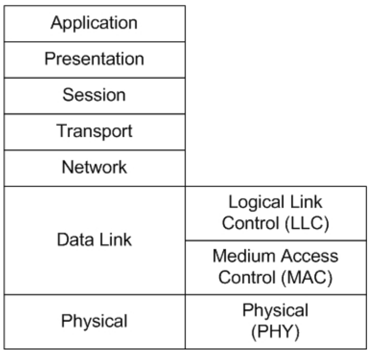


Figure 2.1: The OSI model for IEEE 802

IEEE 802 divides the data link layer into two sublayers, the logical link control (LLC) and the medium access control (MAC) [16]. The LLC is placed above the MAC layer. The LLC offers two different services to the next higher layer, the LLC data service and the LLC management service. The features of the LLC layer are packet segmentation and handshake.

2.1.1 Medium Access Control – MAC

The protocol on this sublayer defines the way the communication channel also called medium is shared among the different users. An example of a shared medium is the medium on which the wireless devices operate, thus the space through which the radio-waves propagate. Therefore the ultimate objective of the MAC sublayer for wireless communication is to allow the large group of normally uncoordinated users to efficiently use the shared medium. The choice of the protocol on this sublayer is thus bound to the nature of the traffic and the performance targeted by the users [16].

In general traffic is classified in two groups: periodic and bursty traffic.

The traffic is called *periodic* when the interarrival variance between messages is very small. For example signals such as voice and video generate periodic traffic. This traffic demands a limit on the maximum end-to-end delay and the delay variation, also called jitter. It is normal that the design of the MAC sublayer has a large influence on the signal delay as the delay depends on the time required to grant the access to the channel. The data rate of a periodic traffic source is nearly constant. Therefore, using a dedicated, circuit-switched connection for the traffic is more than justified.

The second group of traffic, the so-called *bursty* traffic, is characterized by messages of arbitrary length separated by intervals of random duration. An example for bursty traffic is the data communication in an office environment like e-mail and Internet access. Delay and jitter are not important for this kind of traffic. The data rate of a bursty traffic source is also very varying. Compared to the average data rate, the peak data rate is much higher. This indicates that the utilization of the resources will be low if the capacity over a dedicated connection is provided to satisfy the peak demand. Thus packet-switched connections are favorable for bursty traffic.

It is clear that communication systems must support Internet access as well as voice and video, therefore both types of traffic must be handled. This fact makes the design of the MAC sublayer very difficult. Moreover, the wireless channel is the only mean which can coordinate the stations in a network.

Another important fact for the MAC is the law of large numbers, which means that the combined requirements for a large number of users is equal to the sum of the average requirements of each user. It is this average demand that is considered because, with a large number of users, only a fraction of them have to transmit data at any given time. Still, if more than one user tries to transmit simultaneously, it results in a collision. The MAC sublayer must resolve all these problems.

The access methods can be divided into three main categories: contention methods, polling methods, and time-division multiple-access (TDMA) methods.

The *contention method* is also called CSMA, carrier-sense multiple access or listen-before-talk. If a station wants to transmit data, it first listens the channel for a specified interval of time before finally transmitting the packet.

The length of the time interval is randomly chosen within a predefined interval. If the channel is free during this time, the data will be transmitted. If the channel is occupied by another signal, the station waits another randomly defined time period before again sensing the channel. With this method the probability of collision is minimized, but not equal to zero. If two stations, by accident, choose the same time interval, a collision occurs. In the CSMA with collision detection (CSMA/CD), used in the wired Ethernet (IEEE 802.3), the stations stop their transmission when a collision is detected. The protocol requires acknowledgments for each transmission. All data packets which are not acknowledged due to a collision or unsuccessful reception will be sent again. Despite the success of the Ethernet, contention systems have one major disadvantage: there are no delay guarantees. Thus contention system are well-suited for bursty traffic, but are unsuitable for periodic traffic.

In so-called slotted systems as the *TDMA method*, all stations are synchronized and have different time slots of certain duration assigned to them in a periodic cycle. This is obviously best suited for periodic traffic, but for bursty traffic most of the time the channel capacity is wasted, because the station has always a time frame assigned to it even if it does not use it. The main problem for these protocols is the selection of the time slot duration and the packet size. If time slot duration is too long, smaller messages will not use the channel effectively, but if the slot duration is too short bigger messages need several time slots to be transmitted and therefore more time will be needed. Message size change dynamically and cannot be known in advance. The time division mechanism of the TDMA is represented in Figure 2.2.

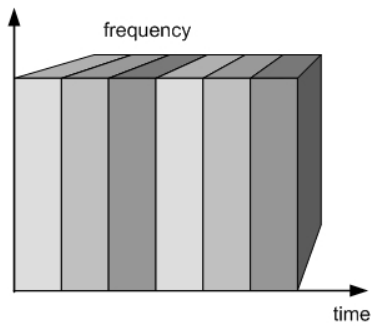


Figure 2.2: TDMA – time-division multiple access

The third type of access methods, the *polling method*, requires a central station. This central station controls the network by polling all individual stations. A station which wants to transmit, does it in response to a poll from the central station. There is also the possibility to transmit periodic data by requesting to be polled on a periodic basis. The central station maintains a global queue of all requests. The polling method is very efficient as it achieves dynamic resource allocation. But there are also several disadvantages. First, the maintaining of the global request queue can have a very high overhead. This overhead is caused by the channel access mechanism and depends on the number of stations unlike the contention schemes. Second, all of the data must pass through the central station, even if it's not destined to it. Third, polling is absolutely not suitable for wireless ad-hoc networks, which never have a central station. The polling principle is demonstrated in Figure 2.3.

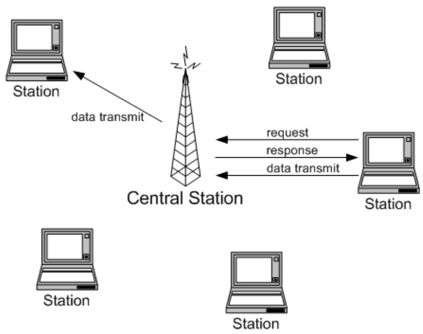


Figure 2.3: Polling

All access protocols are classified as either static or dynamic. An advantage of a static protocol is that each user gets his part of the resources in the network, but these resources cannot be transferred from one user to another. Thus, users who do not have any data to transmit get the same resources as users with data to transmit. In dynamic MAC protocols, the network resources are only allocated to users who have data to transmit. Contention-based MAC protocols are easier to implement than other dynamic-allocation protocols, because of the fact that users can join and leave the network at any time. This feature is very important in wireless networks where stations can roam freely. Generally, dynamic-allocation MACs have better performance than static-allocation MACs for light-to-medium traffic loads. With heavy traffic loads, the static-allocation MAC has a lower end-to-end delay than the dynamic-allocation MAC.

Obviously, the mobility of the different stations affects the wireless communication protocol. There are two classes of stations to differentiate—portable and mobile stations. A portable station can be transported from one point to another, but normally only participate in the network while being in a fixed position. Thus, static or very slowly moving stations can be considered as portable stations. Mobile stations can also participate in the network while being in motion.

Summarized, the MAC in wireless communication needs the following features:

- The MAC protocol has to be independent of the physical layer.
- The access mechanism has to be highly efficient for periodic as well as bursty traffic.
- The MAC has to handle static as well as mobile users.

2.1.2 Physical Layer – PHY

The first of the seven layers in the OSI model is the physical layer, which is responsible for the transport of bits over the air. The PHY mainly has two functionalities, transmit or receive mode, depending on what the device is currently doing. In the transmit mode, the PHY receives a bit stream from the MAC layer and performs signal processing operations like modulation and error-correcting coding to transform the bit stream into an electric signal that is sent by the antenna. After the transmission the signal gets demodulated, decoded and error-corrected to transform the signal into a bit stream again, which is passed to the MAC layer. This is the receive mode of the PHY. In addition to that, the IEEE 802 standards ask the PHY to provide a carrier-sense indication back to the MAC [16].

Typically, the wireless channel produces much more bit errors than the wired channel. Additionally, errors often occur in bursts, which overlap with deep fades on the link. Thus, error-control schemes are very important. These error-control schemes can be classified in three types: block codes, convolutional codes, automatic repeat request (ARQ) schemes.

Most of the error-correcting codes are designed to protect against random errors, but not burst errors. Thus, a technique to reduce the statistical dependence of errors is the interleaving. With interleaving, the symbols within one code block are not transmitted in consecutive order, but are split up and rearranged with other transmitted symbols so that a dense burst of errors is less likely to be found in one individual code block. If this interleaving procedure is executed over a sufficiently long time errors on individual blocks can be made independent. From the practical point of view, the interleaved time interval is limited, because the latency is limited. To finally decide, after the decoding, if there is still an error, cycle redundancy code (CRC) is used.

Generally, the PHY requires bandwidth efficiency and power efficiency. Especially, because of the request for higher data rates, the bandwidth efficiency gets more and more important. The power efficiency varies in importance among the different types of wireless networks. For example, WLANs are used on portable terminals, which are battery-powered only for a limited time. Usually they get their power from AC power sources and thus, power efficiency is not very important. On the other hand, WPANs are used on mobile devices, which need batteries the whole time and therefore, power efficiency is very important.

2.2 The IEEE 802.11 Standard

The success of the Ethernet or IEEE 802.3 and the desire to have a 'wireless Ethernet' were the motivation to create the IEEE 802.11 working group within the IEEE 802. In the beginning it was intended to provide connectivity where wires were impossible to use [16].

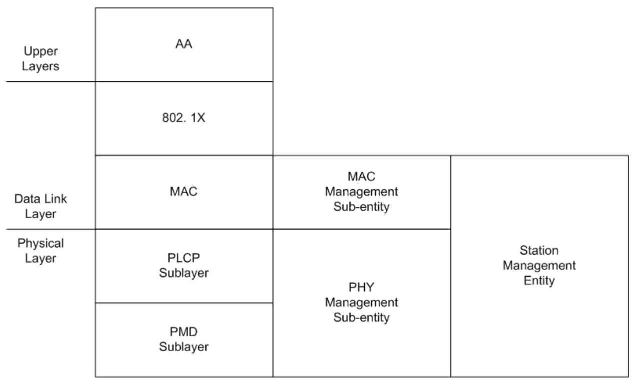


Figure 2.4: General architecture of IEEE 802.11

Figure 2.4 shows clearly the separation of the system into four major parts: the MAC of the data link layer, the PHY, IEEE 802.1X, and upper-layer authentication protocols. The data link layer consists of an IEEE 802.1X layer and a MAC sublayer. The physical layer is built of two sub-layer: a physical layer convergence protocol (PLCP) sublayer and a physical medium-dependent (PMD) sublayer. The PHY and the MAC have management subentities, which communicate with the station management entity.

The medium-access protocol of IEEE 802.11 is the carrier sense multiple access with collision avoidance (CSMA/CA) similar to the CSMA with collision detection used in an Ethernet and will be largely explained in the next chapter. In a wireless environment the collision detection is impossible as a transmitting station cannot reliably detect a collision because the transmitted signal is much stronger than the received signal. The objective of the MAC layer is to make upper layers unaware of the unreliable nature of the wireless environment. This objective is important because the upper layer protocols do not possess the concept of mobility.

The general architecture of IEEE 802.11 is rather easily explained. A logical device that participates in the network is called a station. A station consists of a physical layer and a medium access control layer. The basic network is called a basic service set (BSS). There are two different kinds of BSSs. One is an ad-hoc or independent BSS (IBSS), for example networks built of laptops or cell phones. These networks are short lived. The other one, called simply BSS, is distinguished by the presence of a special station called access point (AP). The AP allows one network to connect with another network, typically a wired network. The backbone network is normally wired, but can be wireless. The AP is simultaneously a member of both networks—the wireless BSS and the backbone network. In a BSS, a station only communicates with the AP, thus all communications must pass through the AP even if the other station is placed in the same BSS. A group of BSSs can be combined to form an extended service set (ESS). The roaming station in an ESS needs a handoff protocol, which defines how the AP has to hand off the connection for stations. An example of an ESS is represented in Figure 2.5.

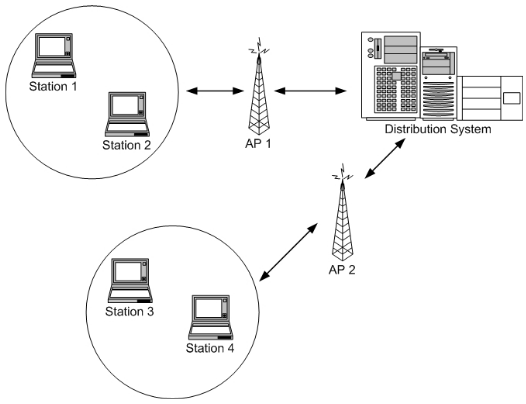


Figure 2.5: Extended service set and distribution system

The IEEE 802.11 standard supports both BSS and IBSS topologies. In a BSS, decision-making is centralized, whereas it is distributed in an IBSS.

The architecture indicates clearly that there are two groups of functions that are called 'services'. The first group is called station services and these are part of every station. The services are key distribution, user (de)authentication, data delivery and authentication, replay protection, and privacy. The second group of functions are the distribution services. These are only used in networks working with access points to manage the traffic.

The services are association, dissociation, distribution, integration, and reassociation. Some of these services are used to control access and provide data confidentiality, others are used to support data delivery between stations.

The MAC layer exchanges three types of messages: data, management, and control. Management messages are used to support the services. Control messages are used to support the delivery of management and data messages.

Chapter 3

Medium-Access Mechanism – CSMA/CA

In this chapter, the different timing intervals that play a role in wireless networks are specified. Then the basic access mechanism for IEEE 802.11, the CSMA/CA protocol, is described.

3.1 Interframe Spaces

Timing is very important for the medium-access protocol. The time interval between different frames is called interframe space (IFS). Five time intervals are defined in the IEEE 802.11 standard [16]. From the shortest to the longest, they are: short IFS (SIFS), point coordination function IFS (PIFS), distributed IFS (DIFS), arbitration IFS (AIFS), and extended IFS (EIFS). They are illustrated in Figure 3.1

The *SIFS* and the slot time are defined by the PHY. One of the main reasons for having a SIFS is that a station can only transmit or receive, but never do both at the same time. In addition, to change from transmit to receive mode and vice versa takes a specific time. This time is called turnaround time. Like this, the SIFS is the sum of the turnaround time of the radio frequency (RF) transceiver, the MAC processing delay, the PHY processing delay, and the RF delay.

The *PIFS* is the SIFS plus one slot time. The slot time is the time needed to accomplish the clear channel assessment, the turnaround, the MAC processing, and the air propagation.

The *DIFS* is SIFS plus two slot times. The DIFS is the time between the start of the contention window and the end of the previous transmission.

The *AIFS* is only used for Quality of Service (QoS) facility and is not treated in this work.

The *EIFS* is the sum of SIFS, DIFS, and the time it takes to transmit an ACK control frame at the PHY's lowest mandatory data rate. The EIFS is always long enough to protect the ACK from collision with a signal from a station that was unable to update its network allocation vector (NAV).

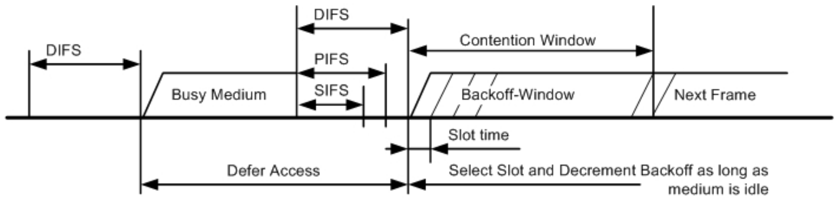


Figure 3.1: The basic access mechanism and interframe space relationships

In Figure 3.1, the relation of the measurement on the medium between the SIFS, PIFS, and DIFS are represented. It is to say that the different interframe spaces are all independent from the bit rate. It is appropriate to see these time periods as specific time gaps on the medium. They are all fixed for each physical layer.

3.2 Coordination Function and CSMA/CA

The coordination function (CF) is a basic concept to the medium-access mechanism. The CF is a logical function, which decides if a station that is operating in a Basic Service Set is allowed to send and receive via the wireless medium. The period of time in which a particular station may initiate transmission on the wireless medium is defined as transmission opportunity. The central access mechanism in the IEEE 802.11 standard is the *carrier sense multiple access with collision avoidance (CSMA/CA)* protocol with exponential backoff. The CSMA/CA protocol is implemented by the DCF, the distributed coordination function. Note that there exist also another CF, the point coordination function (PCF), in which the stations and access points have different roles, but this CF is not treated in this document.

In general the medium-access mechanism defined by the IEEE 802.11 works as follows: before the transmission of data, the station listens if the medium is busy, as shown in Figure 3.1. If the medium is busy, the station does not transmit its data. Actually, the medium should be free for a time period equal to the DIFS if the last frame sent over the medium was received correctly or to the EIFS if the last frame was not received correctly. After this period called idle time, stations which want to send data, will wait another random backoff period before finally transmitting their data. Obviously, this physical carrier sense mechanism decreases the number of collisions to a minimum.

The random backoff time is chosen according to a uniform distribution. The maximum size of the uniform range is called contention window (CW). Thus, the distribution is uniform between 0 and CW. The time unit for this backoff time is named slot time, which is also equal to the round-trip propagation delay. A station senses at each time slot if the channel is busy or not. If the channel is actually free for the duration of the slot, the timer will be reduced by one time slot. If the channel is not free, the timer will not be decremented. Whenever the channel becomes idle again for a time period longer than the DIFS, the backoff process continues from where it was interrupted. This process repeats until the timer can finally count down to zero. Then, the station can begin its data transmission. At the end of it, the station has to wait for an acknowledgment (ACK) from the receiver, to confirm the correct reception. The ACK is always sent after the SIFS to ensure that an ACK is transmitted before the next data packet. No station will sense the channel before the ACK is sent back to the initial transmitter.

The sending station will conclude that an error occurred, if no ACK is received. Errors may occur due to many reasons—collisions, other interference, etc. The recovery of an error is solved by retransmission. The transmitting station augments a retry counter and tries to retransmit. Furthermore, the contention window gets doubled, a new random backoff interval is selected, and the backoff countdown begins again. The backoff is exponential to handle the zero-throughput state, which means that the channel is blocked with retransmissions. Every single station maintains two retry counts, the short retry count and the long retry count, both initialized on zero. The short retry count gets augmented each time the transmission of a short MAC frame, which is a frame whose length is less than or equal to a certain threshold, fails. It will be reset when the transmission of one short MAC frame succeeds. On the other hand, the long retry count is reset whenever the transmission of a long MAC frame succeeds. It will be set to zero again when an ACK frame is received in response to a data transmission of a size bigger than a certain threshold, or when a frame with a group address is sent.

Whenever an unsuccessful trial to send data over the medium provoke a station retry count to increment, the contention window is augmented. It gets incremented until the contention window reaches the maximum specified by the protocol. When it attains this maximum value, the contention window stays at this value until it gets reset. As a result the stability of the access protocol gets improved under high-load traffic. Retransmitted frames can be easily identified by reading the Retry field of the packet, which is set to 1. The retransmission will be continued until the transmission is successful or until the retry limit is reached, whatever comes first. Should the retry counter ever reach its maximum, the retry will immediately cease and the data will be discarded.

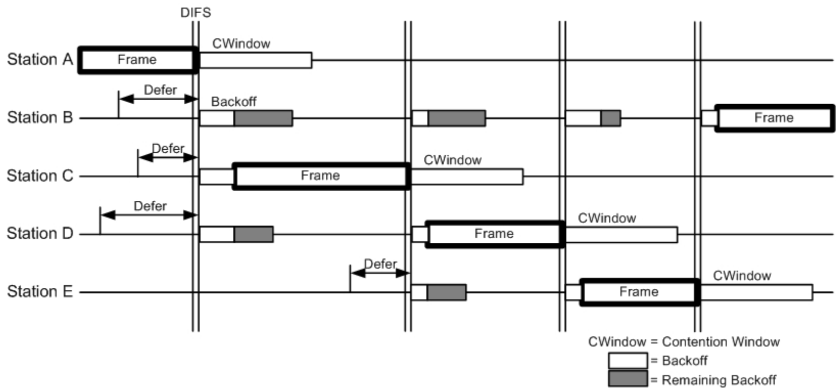


Figure 3.2: Backoff procedure

Figure 3.2 shows the backoff process, which is used when several different stations have to transmit data at the same time. Initially the channel is occupied by station A, and stations B, C, and D defer. After A finished its transmission, B, C, and D will wait another DIFS time and enter the backoff procedure. C wins the contention, because it chooses the shortest backoff interval. While C is transmitting, stations B and D suspend their backoff counters. Station C finishes its transmission, therefore B and D decrement their counters again. Now station D wins the contention and the process continues as represented on Figure 3.2.

In one specific situation, the station does not need to perform the backoff procedure before starting the data transmission. A data packet coming from the next higher layer can be transmitted without waiting, if the last post-backoff has already been finished, i. e. the queue is empty, and the channel has been idle for at least a duration of DIFS. But all the following packets must be sent after the random backoff as usual, until the transmission queue gets empty again.

3.3 Hidden User Phenomenon

One of the biggest problems of wireless networks is the *hidden user phenomenon*. A station may be able to communicate with two other stations, but those two stations may not be able to communicate between themselves.

That may lead to the situation that one of the two stations may sense the channel to be idle, even when there is actually a transmission being executed. Obviously this increases the probability of collisions in the network. The physical carrier sense of the CSMA/CA protocol is not capable to deal with the hidden node problem. However, there is also a virtual carrier sense mechanism. This virtual carrier sense deals with those kinds of problems by a certain reservation mechanism to signal the upcoming use of the channel. Every frame sent on the medium contains timing values, which will be used to maintain specific counters, called network allocation vectors (NAVs), which can be found in every station. The NAVs are implemented as timers, which are consecutively decremented unconditionally. The NAV will be updated by the duration values of all the received MAC headers, not just the frame addresses to a particular station. The station checks its NAV always before listening on the medium with its physical carrier sense mechanism. Like that, the station only tries to transmit whenever the NAV has a value equal to zero, what means that currently there is no transmission on the channel. Therefore, the station selects a random backoff interval whenever either the physical or the virtual carrier sense mechanism senses the medium as currently busy.

3.4 RTS/CTS Mechanism

Another way to help solving the hidden node problem is a mechanism called the *RTS/CTS mechanism*. This mechanism is only optional. With this mechanism the sending and receiving stations can exchange two types of messages, the request-to-send (RTS) and the clear-to-send (CTS) messages. A station that wants to send data, has to send a RTS packet first. The destination of the data answers with a CTS packet. Both of those packets contain the source and destination addresses and the estimated time interval need to complete the transmission and to return the ACK. The RTS/CTS mechanism is shown in Figure 3.3.

A station that is hidden from one station will always receive one packet—the RTS or CTS. Therefore, it knows that the channel will be busy and also the duration of the transmission. The duration will then be stored in the NAV. However, it is easy to see that the RTS/CTS virtual carrier sense mechanism imposes an overhead, which can get significant. Hence, this mechanism is not used for short packets, because their collision probability and retransmission time costs are very small. To decide the size of a packet, the mechanism uses a threshold called the RTS threshold. If a packet is smaller than this RTS threshold, the RTS/CTS mechanism will not be used.

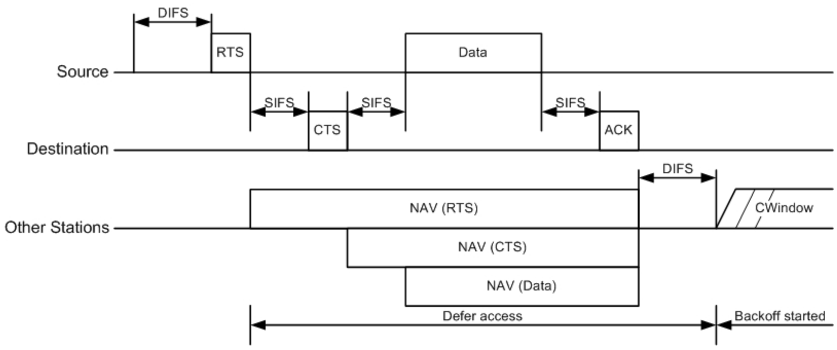


Figure 3.3: Transmission using the RTS/CTS mechanism

Practically, the reservation mechanism is only effective if the stations have the same operating range and note that the RTS/CTS mechanism does not avoid every collision. There may be collisions during the transmission of either the RTS or CTS packet, depending on which packet the hidden node would be able to receive. It is obvious that collisions occur more easily on the transmission of the RTS signal. Finally, this reservation mechanism is also not suitable for broadcasting and multicasting packets. If the transmission of the RTS fails for whatever reason, the mobile short retry count and the access point short retry count are augmented until they reach a specified limit.

Chapter 4

The AODV Protocol

This chapter introduces the *ad-hoc on-demand distance vector (AODV)* protocol and its operation on a wireless ad-hoc network.

The AODV algorithm allows dynamic, self-starting, multihop routing between all mobile nodes participating in a wireless ad-hoc network [12]. AODV enables mobile nodes to receive routes to the desired destination very fast. It does not require the nodes to maintain the routes that are no longer needed in a current communication. AODV allows the nodes to respond very quickly to link breakages and changes in network topology. The operations of AODV are all loop-free, and offer fast convergence when the ad-hoc network topology changes by avoiding the Bellman-Ford 'counting to infinity' problem. Typically, this means when a node changes his position within the network. When a link breaks, AODV notifies all of the concerned nodes so that they are able to avoid and invalidate the routes using this lost link.

One of the most representative features of the AODV protocol is the use of the destination sequence number (DSN) – created by the destination – for each route entry in the routing table of each node participating in the ad-hoc network. The destination sequence number is created by the destination and will be included along with every route information the destination sends to a requesting node. Using the destination sequence numbers assures the so-called 'loop-freedom' and is easy to implement. Given the choice between several routes to a destination, the requesting node has to select the route with the highest sequence number.

The AODV routing protocol is created for mobile ad-hoc networks with tens to thousands of participating mobile nodes. AODV can master low, moderate, and relatively high mobility rates, as well as a variety of data traffic levels. AODV is formed for networks where the nodes can all trust each other, either by the use of preconfigured keys, or because it is known that there are no malicious intruder nodes in the network. AODV has been modeled to minimize the propagation of control traffic and prevent overhead on data traffic, in order to enhance both, the scalability and the performance of ad-hoc networks.

In the following points, the AODV protocol is detailed according to the *RFC 3561* [12]. It gives a short overview to the operation of the protocol as well as the message format of the three message types and some further explanation about the protocol. Note that within the project a simplified version of the AODV protocol has been implemented.

4.1 Protocol Overview

In the AODV protocol, three different types of messages are used, namely the Route Requests (RREQs), the Route Replies (RREPs), and the Route Errors (RERRs). These message types are all transported with UDP, the user datagram protocol, a minimal message-oriented transport layer protocol, and thus the normal Internet protocol (IP) header processing is applied. For example, a requesting node must always use its IP address as the originator IP address for the messages. The IP limited broadcast address (for example, 255.255.255.255 for IPv4) is used for all broadcasting messages. This means that these messages are not just blindly forwarded. Nonetheless, the AODV operations do require several messages (e.g., the RREQ message) to be spread widely through the ad-hoc network. The propagation range of these RREQs is announced by the TTL, the time-to-live, in the header of the IP message. Furthermore, fragmentation is normally not needed.

If the source and destination nodes of a connection have one or more active routes between each other, the AODV protocol remains passive. But whenever a route to a certain destination is required, AODV gets active. The node running AODV broadcasts then a RREQ through the network to find a possible route to a specified destination. This route can be found on two different ways, first, when the RREQ message attains the destination itself, or second, when an intermediate node with a 'fresh enough' route to the destination is joined. The notion of a 'fresh enough' route means a valid route entry for the destination whose related DSN is at least as high as the DSN contained in the concerned RREQ message. The route is activated by unicasting a RREP message back to the source of the RREQ message. Each node in the network, which receives the RREQ message saves a route back to the originator of the request in its routing table. Like this the RREP message can be unicasted from the destination along a path to that originator, or also from any intermediate node that can satisfy the request.

Every node observes the link status of the next hop in an active route.

Whenever one of the links in an active route breaks, a RERR message is sent to notify all other nodes that a break of that link has occurred. The RERR message lists those destinations – destinations which are possibly subnets – which are no longer attainable by the route that contains the broken link. In order to make this reporting mechanism possible, each node maintains a 'precursor list', which contains the IP address for each of its neighbors that possibly could use the node as the next hop towards a specific destination. This information is very easily obtained during the process for the generation of a RREP message, which by definition has always to be sent to a node in a precursor list. Whenever the RREP contains a nonzero prefix length, the originator of the RREQ message, which solicited the RREP message information, is implied among the precursors for the subnet route—not especially for the particular destination.

A node using the AODV protocol can also send a RREQ for a multicast IP address. For example, the source of such a RREQ for a multicast IP address may have to follow specific rules. Anyhow, it is also significant to allow correct multicast operations by intermediate nodes that are not allowed as source or destination nodes for IP multicast addresses, and similarly are not equipped for any special multicast protocol processing. For such multicast-unaware nodes, processing for a multicast IP address as a destination IP address must be carried out in the same way as for any other destination IP address.

AODV is a routing protocol, and thus, it deals also with the routing table management. Routing table information must be maintained even for short-lived routes, such as routes that are created to temporarily store reverse paths towards nodes originating RREQs. AODV uses the following fields with each routing table entry:

- Destination IP Address
- Destination Sequence Number (DSN)
- Valid Destination Sequence Number flag
- Other state and routing flags (e.g., valid, invalid, repairable, being repaired)
- Network Interface
- Hop Count (number of hops needed to reach destination)
- Next Hop

- List of Precursors
- Lifetime (expiration or deletion time of the route)

Destination IP Address	DSN	Valid DSN flag	Other flags			Network Interface	Hop Count	Next Hop	List of Precursors	Lifetime
123.456.789.012	12	0	0	1	0	loO	5	456.789.012.345	...	4
321.654.987.210	45	1	1	0	1	leO	9	456.789.012.345	...	6
456.789.012.345	13	0	1	0	0	loO	3	123.456.789.012	...	7

Figure 4.1: Example of an AODV routing table

Managing the sequence number is very important to assure loop-freedom, especially when links break and a node is no longer reachable to deliver its information about its own sequence number. A destination becomes unreachable when a link breaks or is deactivated. When these conditions are fulfilled, the route is invalidated by operations involving the sequence number and marking the routing table entry state as inoperative.

4.2 Message Formats

In the AODV protocol, three main message types exist: the route request message (RREQ), the route reply message (RREP) and the route error message (RERR). These three types will be explained in the following points along with a special message type, the route reply acknowledgment (RREP-ACK). The message structure is explained to have a better understanding of operation of the protocol, especially concerning the DSN [12].

4.2.1 RREQ Message Format

<table>
<tr><td>Type</td><td>J</td><td>R</td><td>G</td><td>D</td><td>U</td><td>Reserved</td><td>Hop Count</td></tr>
<tr><td colspan="8">RREQ ID</td></tr>
<tr><td colspan="8">Destination IP Address</td></tr>
<tr><td colspan="8">Destination Sequence Number</td></tr>
<tr><td colspan="8">Originator IP Address</td></tr>
<tr><td colspan="8">Originator Sequence Number</td></tr>
</table>

Figure 4.2: Route Request Message – RREQ

The format of the Route Request message is illustrated in Figure 4.2, and contains the following fields:

- J – Join flag; reserved for multicast.
- R – Repair flag; reserved for multicast.
- G – Gratuitous RREP flag; indicates whether a gratuitous RREP should be unicast to the node specified in the Destination IP Address field.
- D – Destination only flag; indicates that only the destination may respond to this RREQ.
- U – Unknown sequence number; indicates that the destination sequence number is unknown.
- Reserved – Sent as 0; ignored on reception.
- Hop Count – The number of hops from the Originator IP Address to the node handling the request.
- RREQ ID – A sequence number uniquely identifying the particular RREQ when taken in conjunction with the originating node's IP address.
- Destination IP Address – The IP address of the destination for which a route is desired.

- Destination Sequence Number – The latest sequence number received in the past by the originator for any route towards the destination.
- Originator IP Address – The IP address of the node which originated the route request.
- Originator Sequence Number – The current sequence number to be used in the route entry pointing towards the originator of the route request.

4.2.2 RREP Message Format

<table>
<tr><td>Type</td><td>R</td><td>A</td><td>Reserved</td><td>Prefix Size</td><td>Hop Count</td></tr>
<tr><td colspan="6">Destination IP Address</td></tr>
<tr><td colspan="6">Destination Sequence Number</td></tr>
<tr><td colspan="6">Originator IP Address</td></tr>
<tr><td colspan="6">Lifetime</td></tr>
</table>

Figure 4.3: Route Reply Message – RREP

The format of the Route Reply message is illustrated in Figure 4.3, and contains the following fields:

- R – Repair flag; used for multicast.
- A – Acknowledgment required.
- Reserved – Sent as 0; ignored on reception.
- Prefix Size – If nonzero, the 5-bit Prefix Size specifies that the indicated next hop may be used for any node with the same routing prefix (as defined by the Prefix Size) as the requested destination.
- Hop Count – The number of hops from the Originator IP Address to the Destination IP Address. For multicast route requests this indicates the number of hops to the multicast tree member sending the RREP.
- Destination IP Address – The IP address of the destination for which a route is supplied.
- Destination Sequence Number – The destination sequence number associated to the route.
- Originator IP Address – The IP address of the node which originated the RREQ for which the route is supplied.
- Lifetime – The time in milliseconds for which nodes receiving the RREP consider the route to be valid.

Note that the Prefix Size allows a subnet router to supply a route for every host in the subnet defined by the routing prefix, which is determined by the IP address of the subnet router and the Prefix Size. In order to make use of this feature, the subnet router has to guarantee reachability to all the hosts sharing the indicated subnet prefix. When the prefix size is nonzero, any routing information (and precursor data) must be kept with respect to the subnet route, not the individual destination IP address on that subnet.

The 'A' bit is used when the link over which the RREP message is sent may be unreliable or unidirectional. When the RREP message contains the 'A' bit set, the receiver of the RREP is expected to return a RREP-ACK message.

4.2.3 RERR Message Format

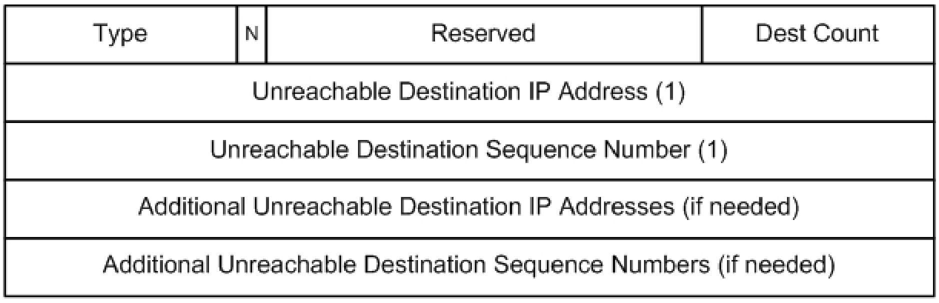


Figure 4.4: Route Error Message – RERR

The format of the Route Error message is illustrated in Figure 4.4, and contains the following fields:

- N – No delete flag; set when a node has performed a local repair of a link, and upstream nodes should not delete the route.
- Reserved – Sent as 0; ignored on reception.
- Dest Count – The number of unreachable destinations included in the message; must be at least 1.
- Unreachable Destination IP Address – The IP address of the destination that has become unreachable due to a link break.
- Unreachable Destination Sequence Number – The sequence number in the route table entry for the destination listed in the previous Unreachable Destination IP Address field.

The RERR message is sent whenever a link break causes one or more destinations to become unreachable from some of the node's neighbors.

4.2.4 Route Reply Acknowledgment Message Format

The Route Reply Acknowledgment (RREP-ACK) message must be sent in response to a RREP message with the 'A' bit set. This is typically done when there is danger of unidirectional links preventing the completion of a route discovery cycle.

Type	Reserved

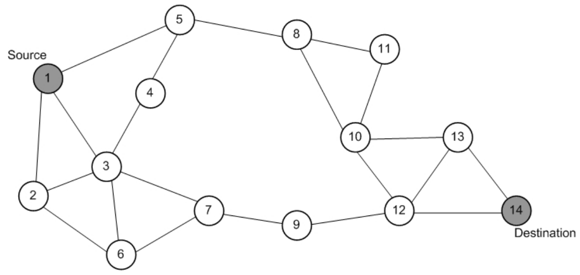
Figure 4.5: Route Reply Acknowledgement – RREP-ACK

The format of the Route Error message is illustrated in Figure 4.5, and contains the following fields:

- Reserved – Sent as 0; ignored on reception.

4.3 AODV Operation Example

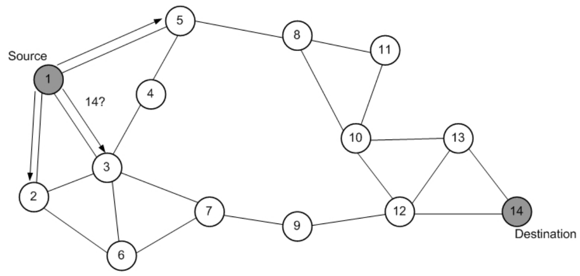
In this section, a detailed example of the main AODV operations, the route request, the reply and the error detection, will be described and illustrated, as explained in [7].



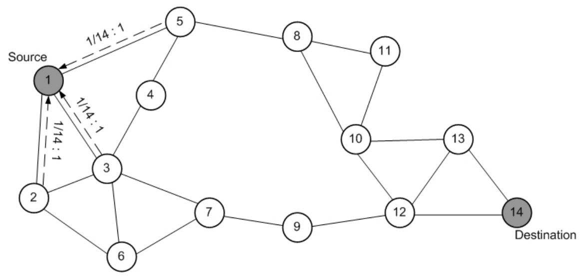
In this ad-hoc network example consisting of 14 active nodes, the node 1 acts as the source of a request and the node 14 as its destination. The request of a route from source to destination starts with the source broadcasting a route request (RREQ) message through the network.

4.3.1 Route Request – RREQ

The source node 1 emits a RREQ message as a broadcast flood request message to the network. All of its neighbors, by name node 2, node 3, and node 5, receive the RREQ with the request for the destination node 14. To do so the source node 1 increments its sequence number and creates the route request message with the destination IP address, the latest received DSN, the originator IP address, and the originator sequence number (OSN) as described in the previous section.

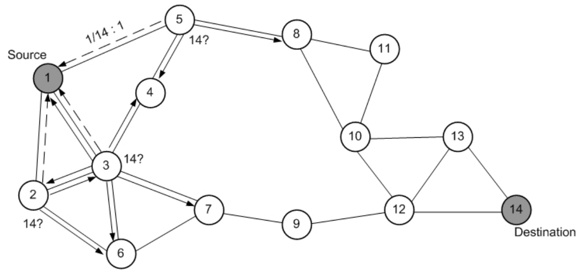


After receiving the RREQ message, but before forwarding it, the request receiving nodes define a reverse route to the source of the RREQ message. This is made by updating the routing table. The routing table entry is indicated on the figure. Note that by receiving the request, the current sequence number of the node is compared to the DSN of the RREQ message. If the sequence number of the node is higher, the RREQ message must be discarded. On the other hand, if the DSN is higher, the current number of the node will be updated by the value of the DSN.

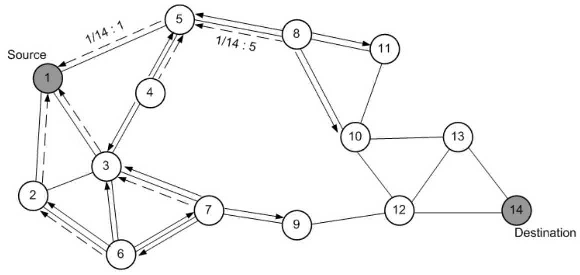


Again the RREQ message is flooded through the ad-hoc network. Node 2, 3, and 5 send the request message to all of their neighbors. Note that the hop count of the RREQ message gets incremented with every hop.

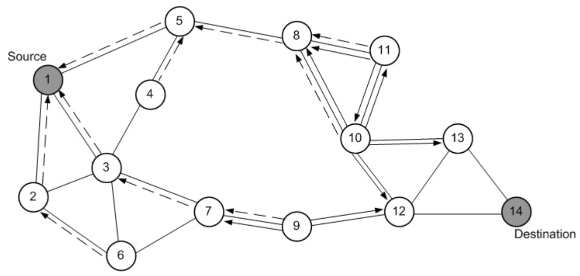
The broadcasting has one major disadvantage, the RREQ message will be replied to their originator too. Therefore, the AODV protocol proposes the following mechanism: nodes who have already received the request simply ignore and discard it due to the destination managed sequence number and



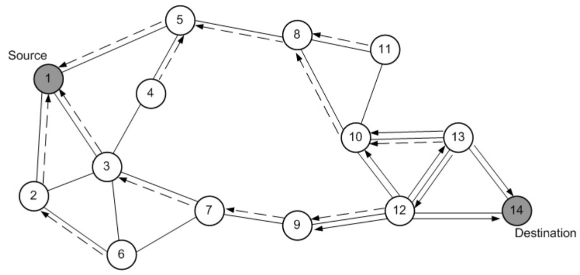
the ID of the RREQ message. This mechanism assures the loop-freedom of the AODV protocol.



The broadcasting of the RREQ message continues and advances slowly to the destination node. Note that the flooding of messages is very expensive and broadcasting can create several collision problems in ad-hoc networks.

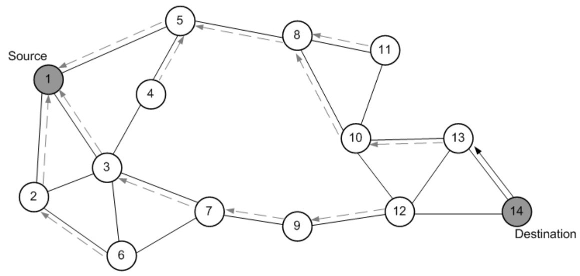


Finally, the RREQ message arrives at his destination. In the example, two different routes are detected.

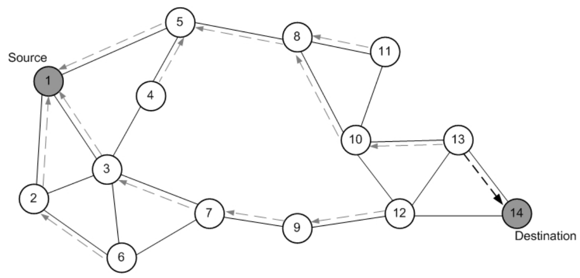


4.3.2 Route Reply – RREP

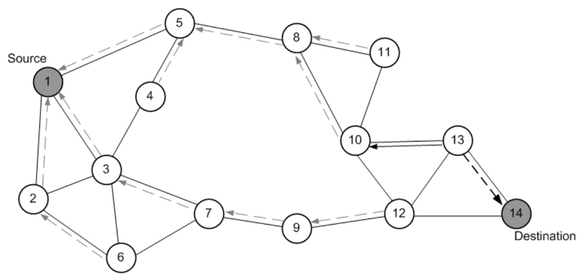
As the destination node 14 received the RREQ message, it will answer it by sending back a route reply (RREP) message to the source node 1.



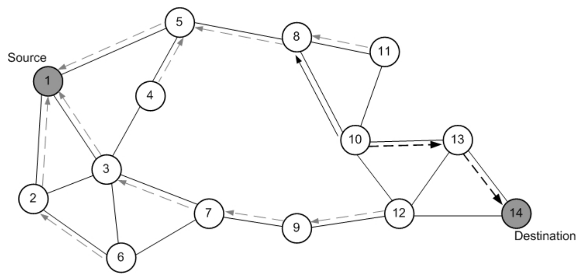
Before sending back a RREP, the destination node updates and increments its sequence number, thus, its DSN. After that it creates the RREP message with the source node 1 for destination. The message will be of the form described in the previous section. The route reply message is always sent as unicast message. Note that the destination chooses the shortest route back to the source by comparing the hop count of the message. The algorithm chooses the route with the next hop being the node 13, as both routes have the same length the choice is made randomly.



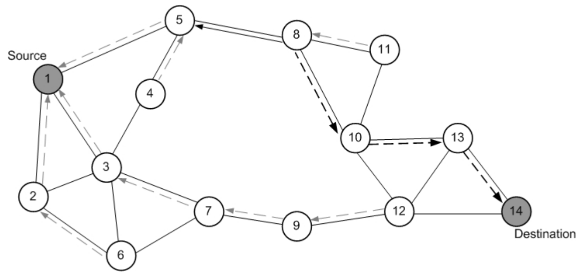
The node 13 receives the RREP message and, after checking the DSN again, updates its routing table by now introducing the forward route to the destination.



The RREP message makes its way through the ad-hoc network by following the reverse route constructed by the RREQ message back to the source of the request.



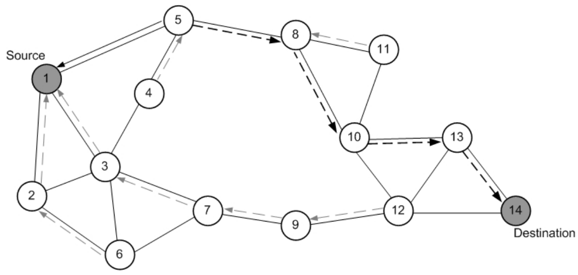
On the way back to the source node 1, each node, through which the RREP message pass, checks the DSN and furthermore, updates its routing table by adding the forward route to the destination into its table.

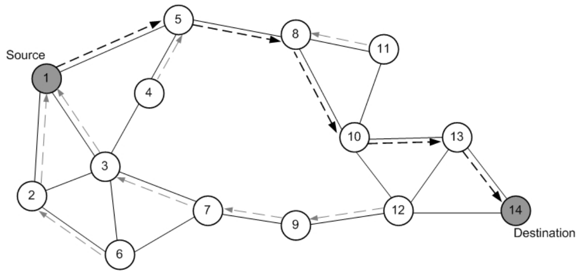


In general, the RREP message is much faster. This is in fact because a standard unicast message does not normally encounter the problems, which a broadcasting message could encounter while flooding through the ad-hoc network. Those problems are shortly listed above.

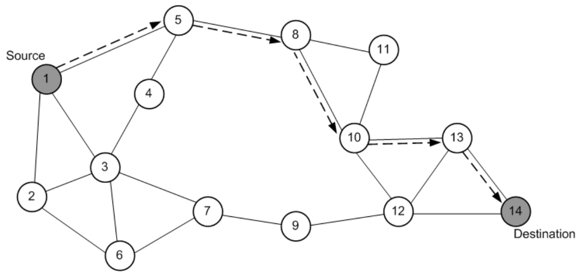
Finally, the RREP message reaches the source node of the route request message and the forward route to the destination node 14 will be completed and ready for the data transfer.

Note that when the source node receive the RREP message, it adopts automatically the current DSN of the route reply message.



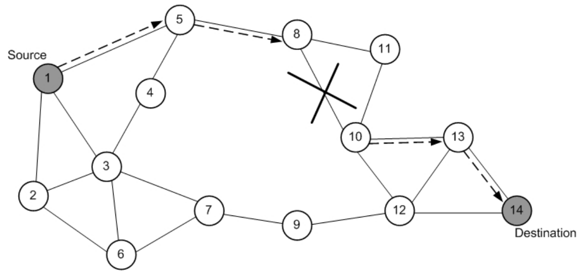


The route from the source node 1 to the destination route 14 is finally created. The data traffic can now flow along the forward route, as long as the current route is still active. The time to live of this forward route will be refreshed at each usage and that of the reverse route simply times out.

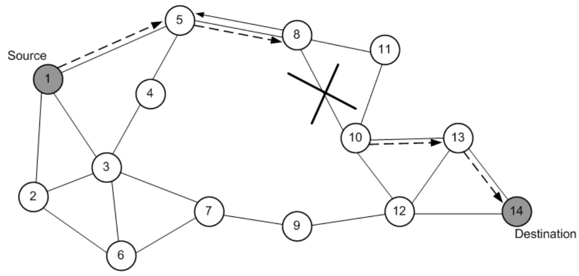


4.3.3 Route Error – RERR

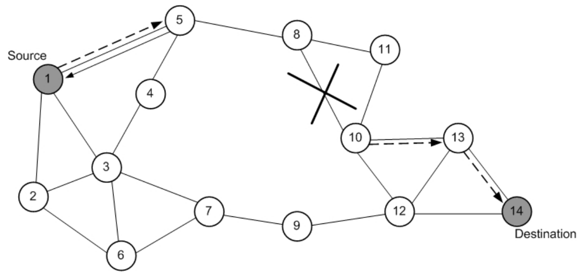
As a last point for the example, the route error detection and recovery will be shortly introduced, by showing what happens when a link breaks, in this example it will be the link between node 8 and 10.



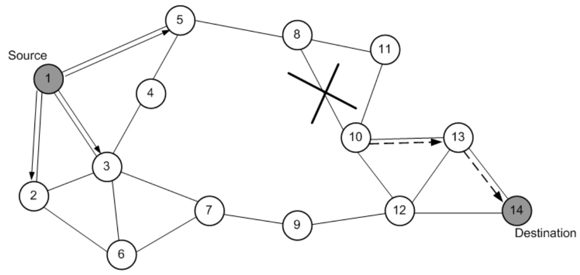
Due to the traffic flow from source node 1 to destination node 14, the node 8 will have to send another data package to the node 10 after the link failure. As the link is broken, node 8 detect the link failure, because the transmission to node 10 fails.



In reaction to the failure detection, node 8 increments its sequence number and creates a route error (RERR) message, which will be returned to the source node of the broken route, in this example, node 1. The RERR will be formatted as mentioned in the previous section.



The RERR message returns now to the source node along the reversed transmission route through the ad-hoc network, until the route error message reaches source node 1.



After receiving the RERR message, source node 1 is obliged to re-initiate the route discovery process by sending a new route request (RREQ) message. The protocol continues as described above. Note that, as soon as the RREQ reaches node 10 or node 13, which have a currently active route to the destination in their routing table, this node will send a route reply (RREP) message back to the source.

This short example illustrates well the general operations of the AODV protocol in an wireless ad-hoc environment. For more detailed information about the protocol and its operations, it is advised to consult the RFC 3561 – Ad-hoc On-Demand Distance Vector (AODV) Routing.

Chapter 5

Antennas and Signal Processing

Antennas in communication systems are the port through which radio frequency (RF) energy is coupled from the transmitter to the outside world and, in reverse, from the outside world to the receiver [13].

More specifically, an antenna is an arrangement of conductors designed to radiate (transmit) an electromagnetic field in response to an applied alternating electromotive force (EMF) and the associated alternating electric current. If an antenna is placed into an electromagnetic field, that field will induce an alternating current upon the antenna, and EMF between its terminals.

However, antennas have always been one of the most unattended of all components in communication systems. Nonetheless, the way in which the energy is distributed into and collected from surrounding space, the so-called medium, has a big influence on the effective use of the spectrum, the cost of establishing new networks, and the service quality provided by those networks.

In this chapter, a short introduction to what antennas are and what parameters mainly influence their performance is given. Furthermore, this chapter explains the basics of signal treatment including the modulation and demodulation process. Note that a more specific look on smart antenna systems is also taken in the following chapter.

5.1 Antenna Systems

There are two fundamental types of antennas. The first type couples to the electric field of an electromagnetic wave, and usually consists of a length of wire in which an electric charge moves back and forth (electric dipole). The second type couples to the magnetic field of an electromagnetic wave, and is usually a coil or loop of wire (magnetic dipole).

By adding additional conducting rods or coils (called elements) and varying their length, spacing and orientation, an antenna with specific desired properties can be created. Typically, antennas are designed to operate in a relatively narrow frequency range. The design criteria for receiving and transmitting antennas differ slightly, but generally an antenna can receive and transmit equally well. This property is called reciprocity.

The vast majority of antennas are simple vertical rods a quarter of a wavelength long. Such antennas are simple in construction, usually inexpensive, and both radiate in and receive from all horizontal directions (omnidirectional). One limitation of this antenna is that it does not radiate or receive in the direction in which the rod points. This region is called the antenna blind cone or null.

Antennas have practical use for the transmission and reception of radio frequency signals (radio, TV, etc.), which can travel over great distances at the speed of light, and pass through nonconducting walls although there is often a variable signal reduction depending on the type of wall. Natural rock can also be very defective to radio signals.

5.1.1 From Omnidirectional to Smart Antennas

Radio antennas couple electromagnetic energy from one medium to another—e.g., wire, coaxial cable, or waveguide. In addition, the physical designs of such antennas can vary importantly. In this section, the evolution of antennas in communication systems is shortly described [13].

In the beginning of wireless communication, there has been the simple dipole antenna, also called *omnidirectional antenna* (see Figure 5.1), which sends and receives equally well in all directions. To locate its users, this single-element designed antenna distributes omnidirectionally in a pattern resembling to ripples radiating outward in a pool of water. While well-working in a simple RF environment where no further knowledge of the users location is available, this unspecific antenna transmits its signals and reaches the desired users with only a small percentage of the overall energy sent out on the medium.

Due to these constraints, omnidirectional antennas try to surmount this challenge by simply amplifying the power level of the signals broadcast. In a network with several different users, and thus interferers, this makes the already not favorable situation worse, because the signals that miss the intended station become interference for those in the same or adjoining radio cells. In uplink applications, i. e. user to a base station, omnidirectional antennas offer no advantageous gain for the signals of served users. In general,

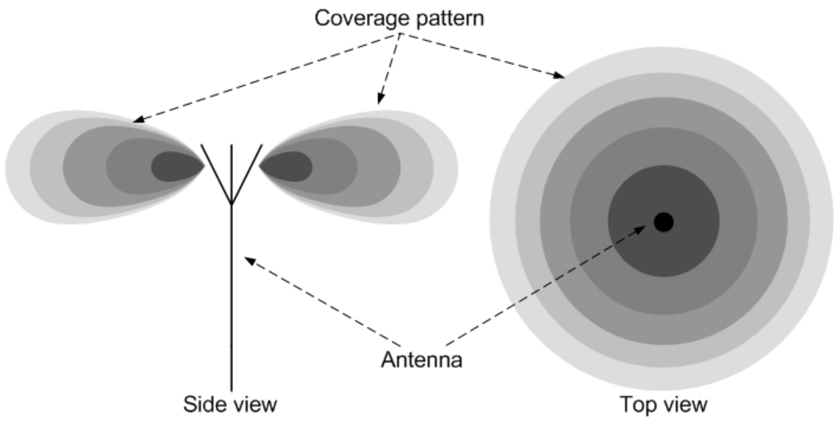


Figure 5.1: Omnidirectional antenna and coverage pattern

users have to shout over the competing signals. Also, this single-element approach cannot selectively reject signals interfering with those of served users and has no spatial multipath interference decrement or equalization capabilities.

Omnidirectional systems have a direct and unfavorable impact on the spectral efficiency, limiting the frequency reuse. These limitations force the system designers to create increasingly elaborated and more costly mechanisms and devices. Lately, these limitations of broadcast antenna technology on the quality, capacity, and coverage of wireless systems have encouraged a rapid evolution in the rudimental design and role of the antenna in a wireless system.

The next type of antenna to cite is the *directional antenna* represented in Figure 5.2. The directional antenna is designed as a single antenna, which is constructed to have certain fixed favored transmission and reception directions. In addition to the brute force method of adding new transmitter sites, many conventional antenna towers today split, or sectorize the cells. A 360° area is often separated into three 120° subareas, each of which is covered by an other broadcast method of transmission. All the other parts being equal to the omnidirectional antenna, sector antennas provide increased gain over a restricted range of azimuths compared to a normal dipole antenna.

This is commonly referred to as antenna element gain and should in no case be confused with the processing gains associated with smart antenna systems. While sectorized antennas increases the overall use of channels, they still cannot overcome the main disadvantages of normal omnidirectional antenna broadcast such as the co-channel interferences.

The essential question of antenna systems design to address now is how

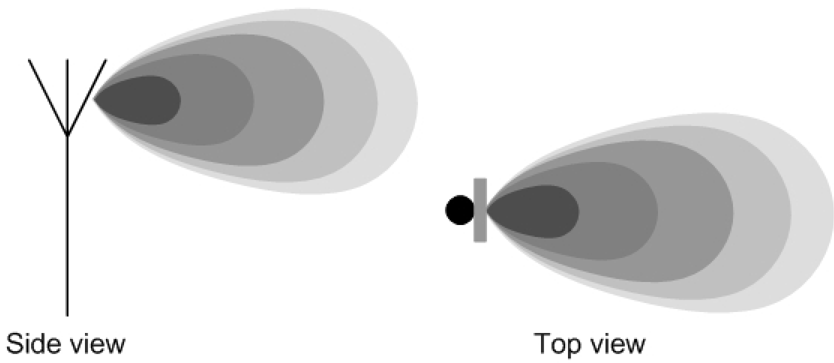


Figure 5.2: Directional antenna and coverage pattern

an antenna can be made smarter. The first idea would be by modifying its physical design by adding more elements. Secondly, an antenna system can be developped to shift the signals before transmission at each of the antenna elements so that these elements have a composite effect. This basic hardware and software concept is known as the phased array antenna.

The following antenna systems summarize the developments in order to increase the benefits and the intelligence of the system.

Sectorized antenna systems (see Figure 5.3) in a usual cellular area split it into different sectors that are covered using directional antennas all located at the same base station. On an operational level, each sector is handled as a different cell, for which the range is greater than in the normal omni-directional system. Sector antennas augment the possible reutilization of a frequency channel in those cellular systems by minimizing potential interference in the original cell, and they are largely used for this intention. Usually, six sectors per radio cell have been used in practical service. When using more than only one of these directional antennas, the base station can cover all directions.

In the next step towards the smart antennas, the diversity system was introduced. This system incorporates two antenna elements at the base station, with a small physical separation, i. e. space diversity, of which has been used to improve reception by counteracting the negative effects of multipath interference.

Diversity offers an enhancement in the effective power of the received signal by using one of the following two methods:

- *Switched diversity* – Supposing that at least one antenna will be in a favorable location at a given moment, this system continually changes between the antennas – switches each of the incoming channels to the best serving antenna – to always utilize the element with the largest

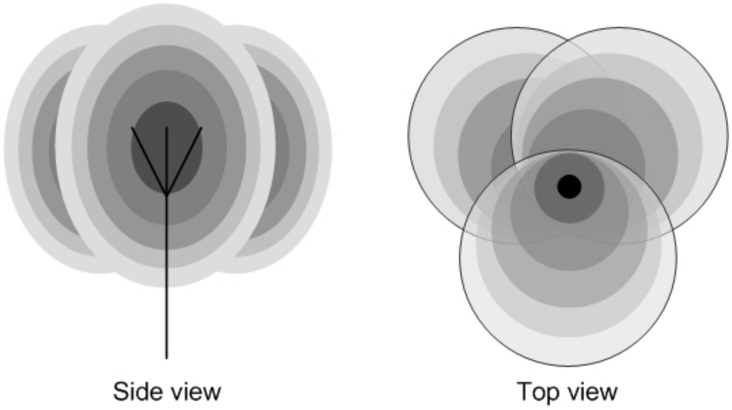


Figure 5.3: Sectorized antenna and coverage pattern

output. They do not increase gain since only one antenna is used at the same time, but they reduce the negative effects of signal fading. For example, the reduced number of black holes in Figure 5.4.

- *Diversity combining* – This method tries to correct the phase error in two multipath signals and efficiently combines the power of both signals to produce a higher gain. Other diversity systems, such as the maximal ratio combining systems, combine the outputs of all antennas to maximize the ratio of combined received signal energy to noise, as shown in Figure 5.5.

Because macrocell-type base stations traditionally put out far more power on the downlink, i. e. base station to user, than mobile terminals can generate on the reverse path, most diversity antenna systems have emerged only to perform in uplink, i. e. user to base station.

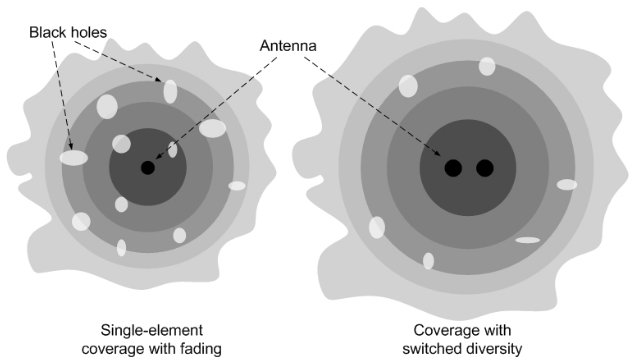


Figure 5.4: Single-element coverage with fading and switched diversity

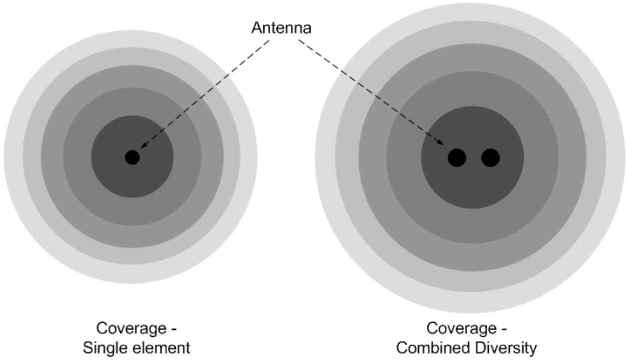


Figure 5.5: Effective coverage pattern with single-element and combined diversity

Diversity antennas simply change operation from one working element to another. Although this approach eases the grave multipath fading, its utilization of one element at a time offers no uplink gain improvement over any other single-element system. In high-interference environments, the simple strategy of locking onto the strongest signal or extracting maximum signal power from the antennas is clearly inappropriate and can result in a clear reception of an interferer rather than the desired signal.

The need to transmit to a number of different users more efficiently without aggravating the interference problem led to the next step of the evolution of antenna systems. The next generation of antennas that intelligently integrate the simultaneous operation of diversity antenna elements, the so-called *smart antennas.*

The concept of using multiple antennas and innovative signal processing to communicate through radio cells more intelligently has already existed for many years. In fact, varying degrees of relatively costly smart antenna systems have been applied in defense systems. Until lately, the elevated costs have prevented their utilization in commercial systems. The introduction of powerful low-cost digital signal processors (DSPs), general-purpose processors, as well as innovative software-based signal-processing algorithms have made smart antennas affordable for cellular communications systems.

Today, when spectrally efficient solutions are increasingly a business imperative, these systems are providing greater coverage area for each cell site, higher rejection of interference, and important capacity improvements.

5.1.2 Performance of Antennas

There are several critical parameters that affect the performance of an antenna and those parameters can be adjusted during the design process. These are resonant frequency, impedance, gain, aperture or radiation pattern, polarization, efficiency and bandwidth. Transmit antennas may also have a maximum power rating, and receive antennas differ in their noise rejection properties [13].

Resonant frequency

The resonant frequency is related to the electrical length of the antenna. This is usually the physical length of the wire multiplied by the ratio of the speed of wave propagation in the wire. Typically an antenna is tuned for a specific frequency, and is effective for a range of frequencies usually centered on that resonant frequency. However, the other properties of the antenna (especially radiation pattern and impedance) change with frequency, so the resonant frequency of the antenna may merely be close to the center frequency of these other more important properties.

Antennas can be made resonant on harmonic frequencies and with lengths that are fractions of the target frequency. Some antenna designs have multiple resonant frequencies, and some are relatively effective over a very broad range of frequencies, the most commonly known type of wide band aerial is the logarithmic or log aerial but its gain is usually much lower than that of a specific or narrower band aerial.

Impedance

As the electric wave travels through the different parts of the antenna system (radio, feed line, antenna, free space) it may encounter differences in impedance. At each interface, some fraction of the wave's energy will reflect back to the source, forming a standing wave in the feed line. The ratio of maximum power to minimum power in the wave can be measured and is called the standing wave ratio (SWR). A SWR of 1:1 is ideal. A SWR of 1.5:1 is considered to be marginally acceptable in low power applications where power loss is more critical, although an SWR as high as 6:1 may still be usable with the right equipment. Minimizing impedance differences at each interface will reduce SWR and maximize power transfer through each part of the antenna system.

Complex impedance of an antenna is related to the electrical length of the antenna at the wavelength in use. The impedance of an antenna can be matched to the feed line and radio by adjusting the impedance of the feed line, using the feed line as an impedance transformer. More commonly, the impedance is adjusted at the load with an antenna tuner, a balun, a matching transformer, matching networks composed of inductors and capacitors, or matching sections such as the gamma match.

Gain

Gain, aperture, and radiation pattern are tightly linked. Gain is measured by comparing an antenna to a model antenna, typically the isotropic antenna which radiates equally in all directions. Often a dipole is also used as a practical reference as the isotropic source cannot be realized in practice, but it has 2.1 dB gain over an isotropic source. Most practical antennas radiate more than the isotropic antenna in some directions and less in others. Gain is inherently directional; the gain of an antenna is usually measured in the direction which it radiates best. Gain is one dimensional.

Aperture is the shape of the 'beam' cross section in the direction of highest gain, and is two dimensional. Sometimes aperture is expressed as a radius of the circle that approximates this cross section or the angle of the cone.

Radiation pattern is the three dimensional plot of the gain, but usually the two dimensional horizontal and vertical cross sections of the radiation pattern are considered. Antennas with high gain typically show side lobes in the radiation pattern. Side lobes are peaks in gain other than the main lobe (the 'beam'). Side lobes have bad impact to the antenna quality whenever the system is being used to determine the direction of a signal, for example in RADAR systems.

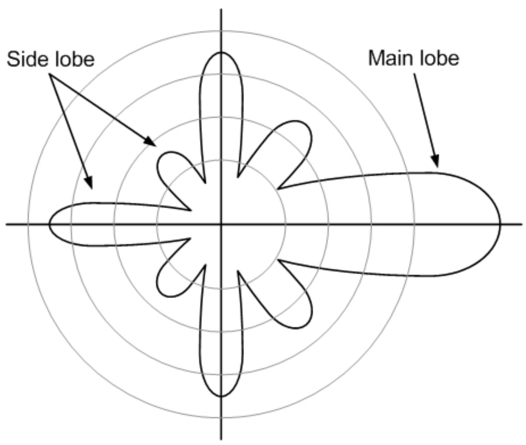


Figure 5.6: Gain of a smart antenna

Efficiency

Efficiency is the ratio of power actually radiated to the power put into the antenna terminals. A dummy load may have a SWR of 1:1 but an efficiency of 0, as it absorbs all power and radiates none, showing that SWR alone is not an effective measure of an antenna's efficiency. Radiation in an antenna is caused by radiation resistance which can only be measured as part of total resistance including loss resistance.

Bandwidth

The bandwidth of an antenna is the range of frequencies over which it is effective, usually centered around the resonant frequency. The bandwidth of an antenna may be increased by several techniques, including using thicker wires, replacing wires with cages to simulate a thicker wire, tapering antenna components (like in a feed horn), and combining multiple antennas into a single assembly and allowing the natural impedance to select the correct antenna.

Of the parameters above, SWR is most easily measured. Impedance can be measured with specialized equipment, as it relates to the complex SWR. Measuring radiation pattern requires a sophisticated setup including significant clear space (enough to get into the far field of the antenna) or an anechoic chamber designed for antenna measurements, careful study of experiment geometry, and specialised measurement equipment such as robots that rotate the antenna during the measurements. Bandwidth depends on the overall effectiveness of the antenna, so all of these parameters must be well comprehended to understand the bandwidth. However, typically bandwidth is measured by only looking at SWR, i.e., by finding the frequency range over which the SWR is less than a given value. Bandwidth over which an antenna exhibits a particular radiation pattern might also be considered.

Polarization

The polarization of an antenna is the polarization of the signals it emits. The ionosphere changes the polarization of signals unpredictably, so for signals which will be reflected by the ionosphere, polarization is not crucial. However, for line-of-sight communications, it can make a tremendous difference in signal quality to have the transmitter and receiver using the same polarization. Polarizations commonly considered are linear, as in vertical, horizontal, and circular, which is divided into right-hand and left-hand circular.

Transmission and receiving

All of these parameters are expressed in terms of a transmission antenna, but are identically applicable to a receiving antenna. Impedance, however, is not applied in an obvious way; for impedance, the impedance at the load (where the power is consumed) is most critical. For a transmitting antenna, this is the antenna itself. For a receiving antenna, this is at the (radio) receiver rather than at the antenna.

Antennas used for transmission have a maximum power rating, beyond which heating, arcing or sparking may occur in the components, which may cause them to be damaged or destroyed. Raising this maximum power rating usually requires larger and heavier components, which may require larger and heavier supporting structures. Of course, this is only a concern for transmitting antennas; the power received by an antenna rarely exceeds the microwatt range.

If an antenna is to be used for reception at very low frequencies (below about ten megahertz), its noise rejection capabilities become important. At such frequencies, signals are reflected very effectively by the ionosphere; however, at these frequencies there are many forms of natural radio noise, including the noise produced by lightning. Successfully rejecting these forms of noise is an important antenna feature. For example, a small coil of wire with many turns is more able to reject such noise than a vertical antenna. However, the vertical will radiate much more effectively on transmit, where unimportant signals are not a concern.

5.2 Signal Propagation

5.2.1 Analogy for Signal Propagation

Imagine a calm pool of water into which a stone is dropped. The waves, which radiate through the water from the point of impact, are uniform and diminish in strength by time. This pure omnidirectional broadcasting is equal to one signal sent by a caller—originating at the terminal and going uplink. It is interpreted as one signal everywhere it propagates.

Now, picture a base station at some distance from the origin of the wave. If the pattern remains undisturbed, it is no difficulty for the base station to receive the waves. But as the waves of the signal begin to rebound on the edge of the pool, they come back, perhaps in a combination of directions, to intersect with the original wave pattern. As they combine, they weaken each other's strength. These are called *multipath interference* problems.

Moreover, imagine that several stones are being dropped in different areas of the pool, that is the equivalent to other calls starting. How could a base station at any particular point in the pool distinguish which signal were being picked up and from which direction? This multiple-source problem is called *co-channel interference*.

These are two-dimensional analogies; to fully comprehend the distinction between callers and/or signal in the atmosphere of the earth, a base station must possess the intelligence to place the information it analyzes in a true spatial context.

5.2.2 Multipath Interference

Multipath is a condition where the transmitted radio signal is reflected by physical structures (see Figure 5.7), creating multiple signal paths between the base station and the user terminal [13].

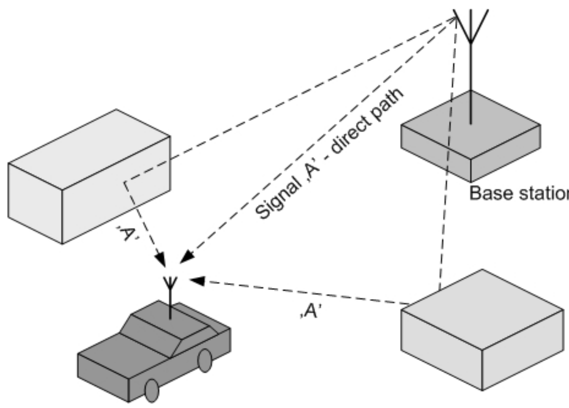


Figure 5.7: Effect of multipath on a mobile user

5.2.3 Problems Associated with Multipath

One problem resulting from having unwanted reflected signals is that the phases of the waves arriving at the receiving station often do not match. The phase of a radio wave is simply an arc of a radio wave, measured in degrees, at a specific point in time. Figure 5.8 shows two out-of-phase signals as they are seen by the receiver.

Conditions caused by multipath that are of important matter are as follows:

- *Fading* – When the waves of multipath signals are out of phase, mitigation of the signal strength can occur. One such type of reduction is

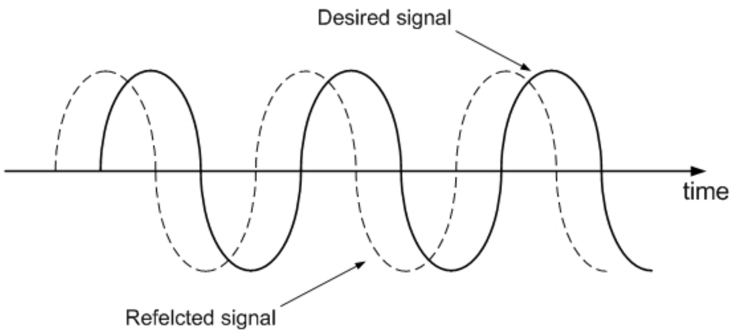


Figure 5.8: Out-of-phase multipath signals

called a fade; the phenomenon is known as 'Rayleigh fading' or 'fast fading' shown in Figure 5.9.

A fade is a constantly changing, three-dimensional phenomenon. Fade zones tend to be small, multiple areas of space within a multipath environment that cause periodic weakening of a received signal for users passing through them. In other words, the received signal strength will fluctuate downward, causing a momentary, but periodic, degradation in quality.

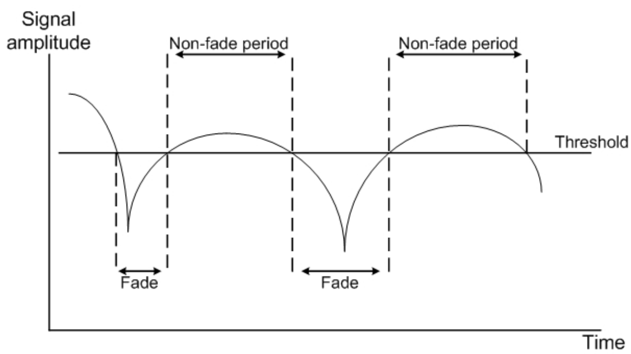


Figure 5.9: Rayleigh fade effect on a user signal

- *Phase cancellation* – When waves of two multipath signals are rotated to exactly 180° out of phase, the signals will cancel each other, as seen in Figure 5.10. While this sounds severe, it is rarely sustained on any given call and most air interface standards are quite resilient to phase cancellation. In other words, a call can be maintained for a certain period of time while there is no signal, although with very poor quality. The effect is of more concern when the control channel signal is canceled out, resulting in a black hole, a service area in which call set-ups will occasionally fail.

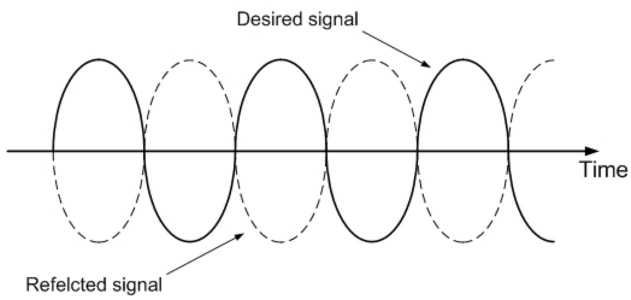


Figure 5.10: Phase cancellation

- *Delay spread* – The effect of multipath on signal quality for a digital air interface (e.g., TDMA) can be slightly different. Here, the main concern is that multiple reflections of the same signal may arrive at the receiver at different times (see Figure 5.11). This can result in intersymbol interference, or bits crashing into one another, that the receiver cannot sort out. When this occurs, the bit error rate rises and eventually causes considerable degradation in signal quality.

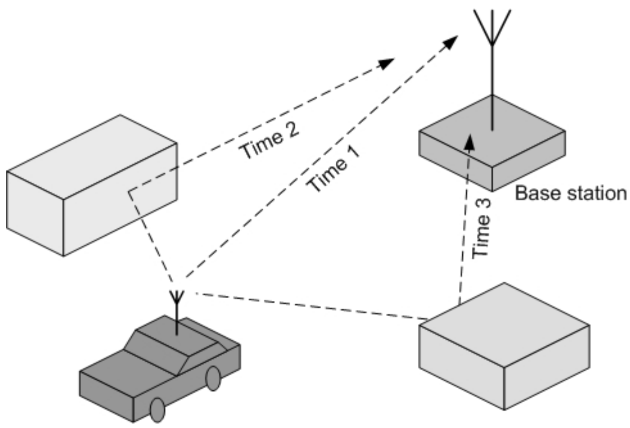


Figure 5.11: Cause of delay spread

While switched diversity and combining systems do improve the effective power of the signal received, their use in the conventional macrocell propagation environment has been typically reverse-path limited due to a power imbalance between base station and mobile unit. This is because macrocell-type base stations have historically put out far more power than mobile terminals were able to generate on the reverse path.

- *Co-channel interference* – One of the primary forms of man-made signal degradation associated with digital radio, cochannel interference occurs when the same carrier frequency reaches the same receiver from two separate transmitters (see Figure 5.12).

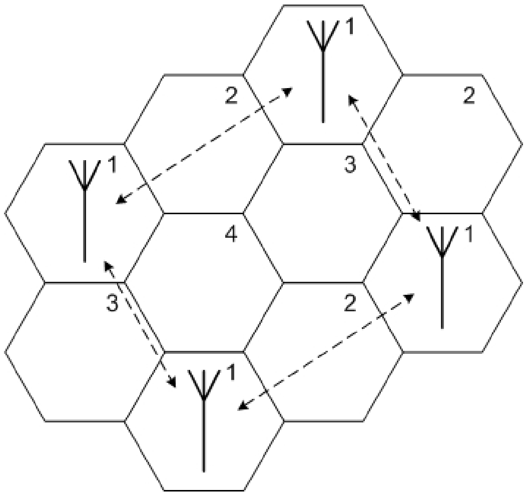


Figure 5.12: Co-channel interference in a typical cellular grid

As shown previously, both broadcast antennas as well as more focused antenna systems disperse signals across relatively wide areas. The signals that miss an intended user can become an interference for users on the same frequency in the same or adjoining cells.

While sectorized antennas multiply the use of channels, they do not overcome the major disadvantage of standard antenna broadcast-co-channel interference. Management of co-channel interference is the number-one limiting factor in maximizing the capacity of a wireless system. To combat the effects of co-channel interference, smart antenna systems not only focus directionally on intended users, but in many cases direct nulls or intentional noninterference towards known and undesired users.

5.3 Signal treatment

In this section, the basic knowledge needed to understand the functioning of signal treatment is explained. This includes the utilization of complex numbers and a short introduction to signal modulation and demodulation of carrier waves. Furthermore, a closer look on the BPSK, the binary phase shift keying, modulation method and on the quantization, a method used to correct errors in a bit sequence, is taken.

5.3.1 Basics

Within this point, the basics of signal treatment needed to understand the content of the project will be given. This contains explanations of complex numbers used as signals, the modulation and demodulation of the signal and the noise added by the medium, while transmission—in this project, the Gaussian noise.

Complex Numbers

A signal that is destined to be transmitted by an antenna is in a mathematical point of view always expressed by a complex number of the form $a+ib$ where a and b are real numbers called the real part and the imaginary part of the complex number, respectively. The imaginary unit $i = \sqrt{-1}$.

The sum and the product of two complex numbers are therefore:

$$(a + ib) + (c + id) = (a + c) + i(b + d)$$

$$(a + ib) \times (c + id) = (ac - bd) + i(bc + ad)$$

The conjugate of a complex number $z = a + ib$ is:

$$\bar{z} = a - ib$$

Complex numbers are used in signal treatment and other fields as a convenient description for periodically varying signals. The absolute value $|z|$ is interpreted as the amplitude and the argument $\arg(z)$ as the phase of a sine wave of given frequency.

If Fourier analysis, which studies the representation of functions or signals as the superposition of basic waves, is employed to write a given real-valued signal as a sum of periodic functions, these periodic functions are often written as the real part of complex valued functions of the form

$$f(t) = ze^{i\omega t}$$

where $\omega = \frac{2\pi}{T} = 2\pi f = v/r$ represents the angular frequency and the complex number z encodes the phase and amplitude as explained above.

In electrical engineering, this is done for varying voltages and currents. The treatment of resistors, capacitors and inductors can then be unified by introducing imaginary frequency-dependent resistances for the latter two and combining all three in a single complex number called the impedance. Note that, electrical engineers and some physicists use the letter j for the imaginary unit since i is typically reserved for varying currents and may come into conflict.

Carrier wave

A carrier wave or carrier signal is a waveform (usually sinusoidal) that is modulated to represent the information to be transmitted. This carrier wave is usually of much higher frequency than the modulating signal, the signal which contains the information.

The reason for this is that it is much easier to transmit a signal of higher frequency, and the signal will travel further.

Carrier waves are used when transmitting radio signals to a radio receiver. Frequency modulation (FM) and amplitude modulation (AM) signals are both transmitted with the help of carrier frequencies. The frequency for a given radio station is actually the carrier wave's center frequency.

In telecommunication, the term carrier or carrier wave has the following meanings:

1. A waveform suitable for modulation by an information-bearing signal.
2. An unmodulated emission. The carrier is usually a sinusoidal wave or a uniform or predictable series of pulses. Synonym: carrier wave.
3. Sometimes employed as a synonym for a carrier system, or a synonym for a telecommunications provider company (operator), such as a common carrier.

Modulation

Modulation describes a range of techniques for encoding information on a carrier signal, typically a sine-wave signal. A device that performs modulation is known as a modulator.

Modulation techniques include:

- Amplitude modulation (AM)
- Phase modulation (PM, includes BPSK, etc.)
- Frequency modulation (FM)
- Different pulse modulation techniques (PCM, PAM, etc.)
- And various other techniques

When transmitting digital data, modulation normally involves shifting one or more properties of the carrier wave between a set of states, a process referred to as keying. This type of modulation includes:

- Amplitude-shift keying (ASK)
- Frequency-shift keying (FSK)
- Phase-shift keying (PSK), like the BPSK
- Gaussian Minimum Shift Keying (GMSK)

Modulation is frequently used in conjunction with various channel access methods.

Demodulation

Demodulation is the act of removing the modulation from an analog signal to receive the original signal. This procedure can produce errors, because while traveling over the medium a noise, for example a Gaussian noise, may be added to the signal.

To demodulate an AM signal, for example, it is passed through a diode rectifier. The amplitude variation will integrate into the original modulating signal.

There are several different ways to demodulate carrier signals. For example, for a FM signal, the most common is to use a discriminator. This is composed of an electronic filter which decreases the amplitude of some frequencies relative to others, followed by an AM demodulator. If the filter response changes linearly with frequency, the final analog output will be proportional to the input frequency, as desired. Another one is to use two AM demodulators, one tuned to the high end of the band and the other to the low end, and feed the outputs into a different amplifier. Another is to feed the signal into a phase-locked loop and use the error signal as the demodulated signal.

The demodulation, used within this project, reverts the operations of the BPSK modulation with aid of the quantization method to correct errors in the received bit sequence.

Gaussian Noise

While transmitting the signal through the medium and while receiving it by an antenna, a noise may be added and thus, the original signal can be modified. Therefore, the incoming signal at the receiver will be

$$r(t) = s(t) + n(t)$$

where $r(t)$ is the received signal, $s(t)$ the original signal, and $n(t)$ the noise added.

The Gaussian noise has a normal probability density function.

The normal distribution, also called Gaussian distribution, is a very important probability distribution in many fields, especially in physics and engineering. It is a family of distributions of the same general form, differing in their location and scale parameters: the mean ('average') and standard deviation ('variability'), respectively.

There are various ways to specify a random variable. The most visual is the probability density function, which represents how likely each value of the random variable is.

The probability density function of the normal distribution with mean μ and variance σ^2 (equivalently, standard deviation σ) is an example of a Gaussian function,

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right)$$

If a random variable X has this distribution, we write $X - N(\mu, \sigma^2)$. If $\mu = 0$ and $\sigma = 1$, the distribution is called the standard normal distribution and the probability density function reduces to

$$f(x) = \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{x^2}{2}\right)$$

5.3.2 Modulation/Demodulation – BPSK

Binary Phase Shift Keying, or BiPhase Shift Keying, (BPSK) is a phase modulation (PM) method for encoding digital data into a carrier wave by variation of its phase in accordance with an input signal.

Note that phase modulation can be regarded as a special case of frequency modulation where the carrier frequency modulation is the time derivative of the PM modulating signal.

Phase-shift keying refers to the simple case of phase modulation by a simple signal with a discrete number of states, such as in morse code or radio teletype applications. For example, with only two states, the technique is Binary Phase Shift Keying (BPSK). With four states, it's known as Quadrature Phase Shift Keying (QPSK), with eight states, it's known as 8-PSK, 16 states is 16-PSK, and so on.

The BPSK method consist generally of encoding and/or transmitting data on top of a carrier. These carriers can be baseband signals, free-space transmissions, or embedded as sub-carriers within the larger context of another signal (e.g., digital audio transmission in PAL-format TV signals).

BPSK is trivially implemented in digital electronics. It has other interesting characteristics as well. For example, the bandwidth of a BPSK signal is precisely that of its data rate, although the generated bandwidth of a BPSK is much wider than its base data rate, analog filters can be employed to narrow the bandwidth down to its base data rate without loss of any data. In addition, its immunity to noise makes it the preferred modulation for many links demanding high reliability, such as long-haul, shortwave radio transmissions, or satellite communications links.

BPSK Principles

Figure 5.13 illustrates how the BPSK modulation method converts a baseband signal into a carrier wave, which can be transmitted over the medium by an antenna. To modulate the signal, the BPSK method consists of converting the phase of the signal and then applying Euler's theorem of complex numbers, notably

$$re^{i\theta} = r(\cos\theta + i\sin\theta)$$

.

Thus, the signal s_0 and s_1 of the Figure 5.13 can be written as

$$s_0 = -A\cos 2\pi f_c t + \phi(t)$$
$$s_1 = A\cos 2\pi f_c t + \phi(t)$$

where f_c is the frequency of the signal.

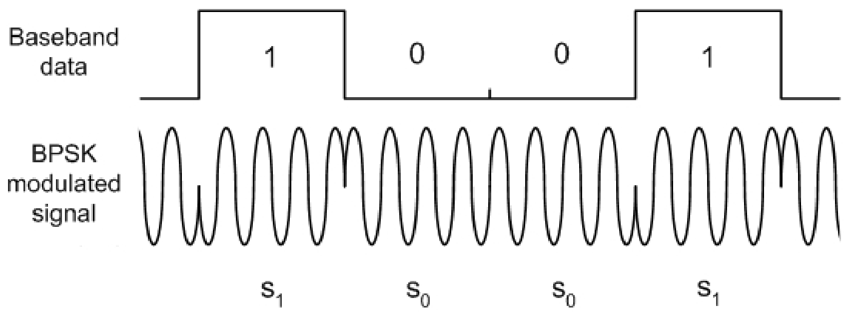


Figure 5.13: BPSK modulation

5.3.3 Quantization

Quantization is the process of approximating a continuous range of values (or a very large set of possible discrete values) by a relatively-small set of discrete symbols or integer values. More specifically, a signal can be multi-dimensional and quantization need not be applied to all dimensions. A discrete signal need not necessarily be quantized.

A common use of quantization is in the conversion of a continuous signal into a discrete signal by sampling and then quantizing. Both of these steps are performed in analog-to-digital converters with the quantization level specified by a number of bits. A specific example would be compact disc (CD) audio which is sampled at 44,100 Hz and quantized with 16 bits (2 bytes) which can be one of 65,536 (216) possible values per sample.

The simplest and best-known form of quantization is referred to as scalar quantization, since it operates on scalar (as opposed to multi-dimensional vector) input data. In general, a scalar quantization operator can be represented as

$$Q(x) = g\left\{round\left[f\left(x\right)\right]\right\}$$

where x is a real number, $i = round\left[f\left(x\right)\right]$ is an integer, and $f(x)$ and $g(i)$ are arbitrary real-valued functions. The integer value $i = round(f(x))$ is the representation that is typically stored or transmitted, and then the final interpretation is constructed using $g(i)$ when the data is later interpreted. The integer value i is sometimes referred to as the quantization index.

In this project, the quantization is used to correct the bit errors occurred while the antenna receives a transmitted signal.

Chapter 6

Smart Antenna Systems

A smart antenna system combines multiple antenna elements with a signal-processing ability to optimize its radiation and/or reception pattern automatically in response to the signal environment [13].

This chapter is a general introduction to the concepts of smart antenna systems and the important advantages of smart antenna system design over conventional omni directional approaches. The chapter also illustrates the various and often varying technologies commonly characterized as smart antennas with a special focus on the adaptive array antenna.

6.1 Analogy for Adaptive Antennas

To more easily understand how an adaptive antenna system works, a short analogy will illustrate the main concept of functioning.

By closing the eyes and speaking with a person moving around in a room, it will be easily noticed that a person can sense the location of another individual without seeing him because of the following:

- Humans hear the speaker's signals through their two ears, the acoustic sensors.
- The voice arrives at each ear at a different time.
- The human brain, functioning as a signal processor, does a large number of calculations to treat the information and compute the location of the speaker.
- Moreover, the brain adds the strength of the signals from each ear together, so that a person perceive sound in one chosen direction as being twice as loud as everything else.

Adaptive antenna systems do the same work in a similar way, using antennas instead of the ears. Obviously, 8, 10, or 12 ears can be used to help the fine-tuning and turning up of the signal information. Furthermore, because both antennas can send and receive – listen and talk –, an adaptive antenna system can send signals back in the same direction from which they came. This means that beside only hearing 8 or 10 or 12 times louder, antenna systems also talk back more loudly and directly.

Also, if additional speakers join in the conversation, the internal signal processor could also cut-out unwanted noise, so-called interference, and alternately focus on one conversation at a time. Thus, advanced adaptive array systems have a similar ability to differentiate between desired and undesired signals on the medium.

6.2 Types of Smart Antenna Systems

In general, antennas are said to be smart, but in reality, these are the antenna systems, which are smart [13]. Generally co-located with a base station, a smart antenna system combines an antenna array with a digital signal-processing capability to transmit and receive in an adaptive and spatially sensitive way. In other words, such a system can automatically change the directionality of its radiation pattern in response to its signal environment. This can significantly enhance the performance characteristics, like the capacity, of a wireless ad-hoc system.

Today, there are terms commonly heard that involve various concepts of a smart antenna system technology include intelligent antennas, phased array, space-division multiple access (SDMA), spatial processing, digital beamforming, adaptive antenna systems, and others. Smart antenna systems are typically categorized, however, as either switched beam or adaptive array systems.

The following are distinctions between the two major categories of smart antennas regarding the choices in transmit strategy:

- *Switched beam* – A finite number of fixed, predefined patterns or combining strategies, i. e. sectors.

- *Adaptive array* – An infinite number of patterns that are adjusted in real time depending on the scenario.

Switched Beam Antennas

Switched beam antenna systems form multiple fixed beams with increased sensitivity in particular directions. These antenna systems detect signal power, choose from one of several predetermined, fixed beams, and switch from one beam to another as the mobile node moves through the sector. Instead of shaping the directional antenna pattern with the properties and physical design of a single element like that of a sectorized antenna, switched beam systems combine the outputs of multiple antennas in such a way as to form finely directional beams with more spatial selectivity than can be achieved with conventional, single-element approaches. The switched beam antenna is illustrated in the Figure 6.1.

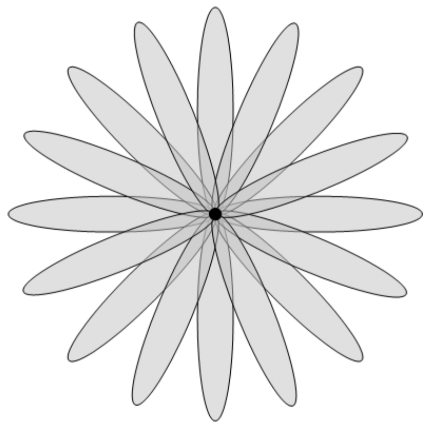


Figure 6.1: Switched beam antenna coverage patterns

Adaptive Array Antennas

Adaptive antenna technology represents the most advanced smart antenna system today. Using a variety of new signal-processing algorithms, the adaptive system takes advantage of its ability to effectively locate and track various types of signals to dynamically minimize interference and maximize intended signal reception. The adaptive array antenna is shown in the Figure 6.2, an illustration of a main lobe extending toward a user with a null directed towards a co-channel interferer.

Both systems attempt to increase gain according to the position of the user. However, only the adaptive system provides optimal gain while simultaneously identifying, tracking, and minimizing interfering signals.

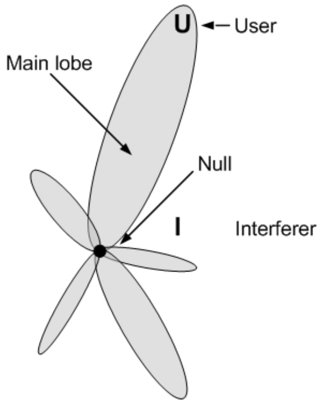


Figure 6.2: Adaptive array antenna coverage

Omnidirectional antennas are obviously distinguished from their intelligent counterparts by the number of antennas, or antenna elements employed. Switched beam and adaptive array systems, however, share many hardware characteristics and are distinguished primarily by their adaptive intelligence.

To process information, which is directionally sensitive, requires an array of 4 to 12 antenna elements, from which the inputs are combined to control signal transmission adaptively. Antenna elements can be arranged in linear, circular, or planar configurations and are most often installed at the base station, although they may also be used in mobile phones or laptop computers.

A simple antenna works for a simple RF environment. Smart antenna solutions are required as the number of users, interference, and propagation complexity grow. Their intelligence is located in their digital signal-processing mechanism.

Similar to most of the modern processing in electronics today, the digital format for manipulating the RF data offers many advantages in terms of accuracy and flexibility of functioning. Communication starts and ends as digital information. Along the way, however, smart antenna systems capture, convert, and modulate digital signals for transmission as analog signals and reconvert and demodulate them to digital information on the other end.

In adaptive antenna systems, this fundamental signal-processing capability is augmented by advanced algorithms, the so-called adaptive filters, that are applied to control operation in the presence of complicated combinations of operating conditions, e. g. the LMS algorithm that will be presented in this document.

The benefit of maintaining a more specified and efficient use of the power of a system and spectrum allocation can be important.

6.3 Goals of a Smart Antenna System

The main objectives of smart antenna systems are to augment the signal quality of the radio-based system through more focused transmission of radio signals and to enhance the capacity by increasing frequency reuse [13]. More specifically, the features of and benefits derived from a smart antenna system include those listed in the following table.

Feature	**Benefit**
Signal gain – Inputs from multiple antennas are combined to optimize available power required to establish the given level of coverage.	*Better range/coverage* – Focusing the energy sent out into the cell increases base station range and coverage. Lower power requirements also enable a greater battery life and smaller/lighter handset size.
Interference rejection – Antenna pattern can be generated towards co-channel interference sources, improving the signal-to-interference ratio of the received signals.	*Increased capacity* – Precise control of the signal nulls quality and the mitigation of interference combine to frequency reuse reduce distance or cluster size, improving capacity. Certain adaptive technologies, such as space division multiple access (SDMA), support the reuse of frequencies within the same cell.
Spatial diversity – Composite information from the array is used to minimize fading and other undesirable effects of multipath propagation.	*Multipath rejection* – Can reduce the effective delay spread of the channel, allowing higher bit rates to be supported without the utilization of an equalizer.
Power efficiency – Combines the inputs to multiple elements to optimize available processing gain in the downlink—towards the user.	*Reduced expense* – Lower amplifier costs, power consumption, and higher reliability will be the result.

6.4 Architecture of Smart Antenna Systems

Traditional switched beam and adaptive array systems enable a base station to customize the beams they generate for each remote user effectively by means of internal feedback control. In general, each method forms a main lobe toward individual users and tries to reject interference or noise from outside of the main lobe.

6.4.1 Listening to the Cell – Uplink Processing

It is supposed here that a smart antenna is only employed at the base station and not at the handset or subscriber unit. Such remote radio terminals transmit using omnidirectional antennas, leaving it to the base station to selectively separate the desired signals from interference selectively.

Typically, the received signal from the spatially distributed antenna elements is multiplied by a weight, a complex adjustment of an amplitude and a phase. These signals are combined to yield the array output. An adaptive algorithm controls the weights according to predefined objectives. For a switched beam system, this may be primarily maximum gain; for an adaptive array system, other factors may receive equal consideration. These dynamic calculations enable the system to change its radiation pattern for optimized signal reception.

6.4.2 Speaking to the Users – Downlink Processing

The task of transmitting in a spatially selective manner is the major basis for differentiating between switched beam and adaptive array systems. As described below, switched beam systems communicate with users by changing between preset directional patterns, largely on the basis of signal strength. In comparison, adaptive arrays attempt to understand the RF environment more comprehensively and transmit more selectively.

The type of downlink processing used depends on whether the communication system uses time division duplex (TDD), which transmits and receives on the same frequency or frequency division duplex (FDD), which uses separate frequencies for transmitting and receiving. In most FDD systems, the uplink and downlink fading and other propagation characteristics may be considered independent, whereas in TDD systems the uplink and downlink channels can be considered reciprocal. Hence, in TDD systems uplink channel information may be used to achieve spatially selective transmission. In FDD systems, the uplink channel information cannot be used directly and other types of downlink processing must be considered.

6.4.3 Switched Beam Systems

In terms of radiation patterns, switched beam is an extension of the current microcellular or cellular sectorization method of splitting a typical cell. The switched beam approach further subdivides macrosectors into several

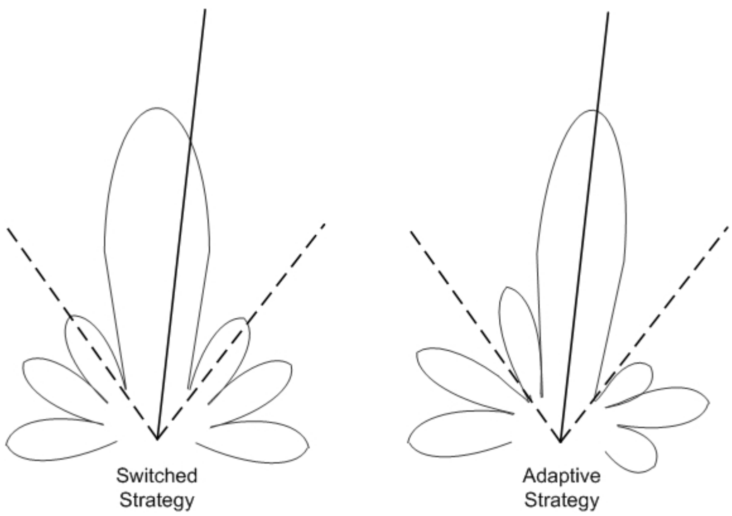


Figure 6.3: Beamforming lobes and nulls that smart antenna systems might choose for user signals and co-channel interferers

microsectors as a means of improving range and capacity. Each microsector contains a predetermined fixed beam pattern with the greatest sensitivity located in the center of the beam and less sensitivity elsewhere. The design of such systems involves high-gain, narrow azimuthal beamwidth antenna elements.

The switched beam system selects one of several predetermined fixed-beam patterns, based on weighted combinations of antenna outputs, with the greatest output power in the remote user's channel. These choices are driven by RF or baseband DSP hardware and software. The system switches its beam in different directions throughout space by changing the phase differences of the signals used to feed the antenna elements or received from them. When the mobile user enters a particular macrosector, the switched beam system selects the microsector containing the strongest signal. Throughout the call, the system monitors signal strength and switches to other fixed microsectors as required.

Smart antenna systems communicate directionally by forming specific antenna beam patterns. When a smart antenna directs its main lobe with enhanced gain in the direction of the user, it naturally forms side lobes and nulls or areas of medium and minimal gain respectively in directions away from the main lobe. Different switched beam and adaptive smart antenna systems control the lobes and the nulls with varying degrees of accuracy and flexibility.

6.4.4 Adaptive Antenna Systems

The adaptive antenna systems approach communication between a user and base station in a different way, in effect adding a dimension of space. By adjusting to an RF environment or the spatial origin of signals as it changes, adaptive antenna technology can dynamically alter the signal patterns to near infinity to optimize the performance of the wireless system.

Adaptive arrays utilize sophisticated signal-processing algorithms to continuously distinguish between desired signals, multipath, and interfering signals as well as calculate their directions of arrival. This approach continuously updates its transmit strategy based on changes in both the desired and interfering signal locations. The ability to track users smoothly with main lobes and interferers with nulls ensures that the link budget is constantly maximized because there are neither microsectors nor predefined patterns.

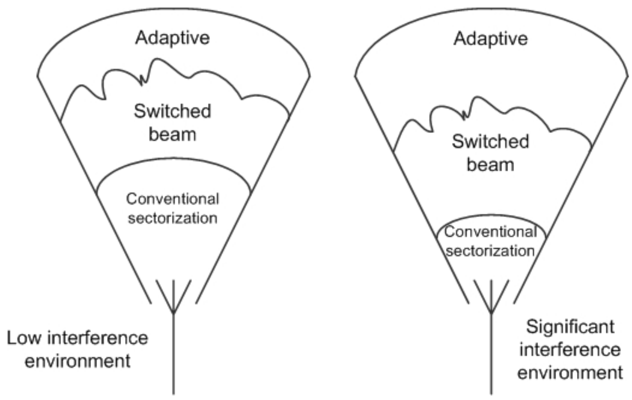


Figure 6.4: Coverage patterns for switched beam and adaptive array antennas

Figure 6.4 illustrates the relative coverage area for conventional sectorized, switched beam, and adaptive antenna systems. Both types of smart antenna systems provide significant gains over conventional sectored systems. The low level of interference on the left represents a new wireless system with lower penetration levels. The significant level of interference on the right represents either a wireless system with more users or one using more aggressive frequency reuse patterns. In this scenario, the interference rejection capability of the adaptive system provides significantly more coverage than either the conventional or switched beam system.

6.4.5 Relative Benefits/Tradeoffs of Smart Antennas

- *Integration* – Switched beam systems are normally designed to retrofit widely deployed cellular systems. It has been commonly implemented as an add-on or application technology that intelligently addresses the needs of mature networks. In comparison, adaptive array systems have been deployed with a more fully integrated approach that offers less hardware redundancy than switched beam systems but requires new build-out.

- *Range/coverage* – Switched beam systems can increase base station range from 20 to 200 percent over conventional sectored cells, depending on environmental circumstances and the hardware/software used. The added coverage can save an operator substantial infrastructure costs and means lower prices for consumers. Also, the dynamic switching from beam to beam conserves capacity because the system does not send all signals in all directions. In comparison, adaptive array systems can cover a broader, more uniform area with the same power levels as a switched beam system.

- *Interference suppression* – Switched beam antennas suppress interference arriving from directions away from the active beam's center. Because beam patterns are fixed, however, actual interference rejection is often the gain of the selected communication beam pattern in the interferer's direction. Also, they are normally used only for reception because of the system's ambiguous perception of the location of the received signal (the consequences of transmitting in the wrong beam being obvious). Also, because their beams are predetermined, sensitivity can occasionally vary as the user moves through the sector.

  Switched beam solutions work best in minimal to moderate co-channel interference and have difficulty in distinguishing between a desired signal and an interferer. If the interfering signal is at approximately the center of the selected beam and the user is away from the center of the selected beam, the interfering signal can be enhanced far more than the desired signal. In these cases, the quality is degraded for the user.

  Adaptive array technology currently offers more comprehensive interference rejection. Also, because it transmits an infinite, rather than finite, number of combinations, its narrower focus creates less interference to neighboring users than a switched-beam approach.

- *Space division multiple access (SDMA)* – Among the most sophisticated utilizations of smart antenna technology is SDMA, which employs advanced processing techniques to, in effect, locate and track fixed or mobile terminals, adaptively steering transmission signals toward users

> and away from interferers. This adaptive array technology achieves superior levels of interference suppression, making possible more efficient reuse of frequencies than the standard fixed hexagonal reuse patterns. In essence, the scheme can adapt the frequency allocations to where the most users are located.

Utilizing highly sophisticated algorithms and rapid processing hardware, spatial processing takes the reuse advantages that result from interference suppression to a new level. In essence, spatial processing dynamically creates a different sector for each user and conducts a frequency/channel allocation in an ongoing manner in real time.

Adaptive spatial processing integrates a higher level of measurement and analysis of the scattering aspects of the RF environment. Whereas traditional beam-forming and beam-steering techniques assume one correct direction of transmission toward a user, spatial processing maximizes the use of multiple antennas to combine signals in space in a method that transcends a one user-one beam methodology.

Chapter 7

Adaptive Filtering

An adaptive filter is a digital filter that performs digital signal processing and can adapt its performance based on the input signal. By way of contrast, a non-adaptive filter has static filter coefficients, which collectively form the transfer function.

For some applications, adaptive coefficients are required since some parameters of the desired processing operation (for instance, the properties of some noise signal) are not known in advance. In these situations it is common to employ an adaptive filter, which uses feedback to refine the values of the filter coefficients and hence its frequency response.

Generally speaking, the adaptive process involves the use of a cost function, which is a criterion for optimum performance of the filter (for example, minimizing the noise component of the input), to feed an algorithm, which determines how to modify the filter coefficients to minimize the cost on the next iteration.

As the power of digital signal processors has increased, adaptive filters have become much more common and are now routinely used in devices such as mobile phones and other communication devices, camcorders and digital cameras, and medical monitoring equipment.

Example of Application

Suppose a hospital is recording a heart beat (an ECG), which is being corrupted by a 50 Hz noise—the frequency coming from the power supply in many countries.

One way to remove the noise is to filter the signal with a notch filter at 50 Hz. However, due to slight variations in the power supply to the hospital, the exact frequency of the power supply might hypothetically wander between 47 Hz and 53 Hz. A static filter would need to remove all the frequencies between 47 and 53 Hz, which could excessively degrade the quality of the ECG since the heart beat would also likely have frequency components in the rejected range.

To circumvent this potential loss of information, an adaptive filter could be used. The adaptive filter would take input both from the patient and from the power supply directly and would thus be able to track the actual frequency of the noise as it fluctuates. Such an adaptive technique generally allows also filters with a smaller rejection range, which means, in our case, that the quality of the output signal is more accurate for medical diagnosis.

7.1 The LMS Algorithm

The *least mean square* error (LMS) algorithm, or Widrow-Hoff learning algorithm, is the simplest and the most universally applicable adaptive filtering algorithm [8]. This algorithm is used for descending on the performance surface and updating the weights of all elemental antennas of an adaptive array antenna. It uses a special estimation of the gradient that is valid for the adaptive linear combiner. The LMS algorithm is important because of its simplicity and ease of computation, and because it does not require off-line gradient estimations or repetitions of data. If the adaptive system is an adaptive linear combiner, and if the input vector $x[k]$ and the desired response $y[k]$ are available at all iteration, the LMS algorithm is generally the best choice for many different applications of adaptive signal processing.

7.1.1 Mean Square Error

The LMS algorithm is an example of supervised training, in which the learning rule is provided with a set of examples of desired network behavior.

$$\{x_1, r_1\}, \{x_2, r_2\}, ..., \{x_n, r_n\}$$

Here y_i is an input to the network, and r_i is the corresponding target output. As each input is applied to the network, the network output is compared to the target. The error is calculated as the difference between the target output and the network output. We want to minimize the average of the sum of these errors.

$$mse = \frac{1}{n}\sum_{i=1}^{n} e(i)^2 = \frac{1}{n}\sum_{i=1}^{n} (r(i) - x(i))^2$$

The LMS algorithm adjusts the weights and biases of the adaptive array antenna so as to minimize this mean square error.

Fortunately, the mean square error performance index for the network is a quadratic function. Thus, the performance index will either have one global minimum, a weak minimum, or no minimum, depending on the characteristics of the input vectors. Specifically, the characteristics of the input vectors determine whether or not a unique solution exists.

7.1.2 LMS Algorithm

The standard LMS algorithm on the k^{th} iteration is defined as follows:

$$W(k+1) = W(k) + \mu x(k) e^*(k)$$

where $W(k)$ is the matrix of the weights, μ the step size of the algorithm, $x(k)$ the k^{th} position of the input vector and $e^*(k)$ the k^{th} position of the error vector.

The LMS algorithm, or Widrow-Hoff learning algorithm, is based on an approximate steepest descent procedure. The algorithm has been developed as follows:

Widrow and Hoff had the insight that it would be possible to estimate the mean square error by using the squared error at each iteration. Assuming the partial derivative of the squared error with respect to the weights w and biases b at the k^{th} iteration, we have

$$\frac{\delta e^2(k)}{\delta w_{1,j}} = 2e(k)\frac{\delta e(k)}{\delta w_{1,j}}$$

for $j = 1, 2, ..., R$ and

$$\frac{\delta e^2(k)}{\delta b} = 2e(k)\frac{\delta e(k)}{\delta b}$$

Next look at the partial derivative with respect to the error.

$$\frac{\delta e^2(k)}{\delta w_{1,j}} = \frac{\delta\left[r(k) - y(k)\right]}{\delta w_{1,j}} = \frac{\delta}{\delta w_{1,j}}\left[r(k) - (W_p(k) + b)\right]$$

or

$$\frac{\delta e^2(k)}{\delta w_{1,j}} = \frac{\delta}{\delta w_{1,j}}\left[r(k) - \left(\sum_{i=1}^{R} w_{1,j} x_i(k) + b\right)\right]$$

Here $x_i(k)$ is the i^{th} element of the input vector at the k^{th} iteration.
Similarly,

$$\frac{\delta e^2(k)}{\delta w_{1,j}} = -x_j(k)$$

This can be simplified to

$$\frac{\delta e^2(k)}{\delta w_{1,j}} = -x_j(k)$$

and

$$\frac{\delta e^2(k)}{\delta b} = -1$$

Finally, the change to the weight matrix and the bias will be $2\alpha e(k)x(k)$ and $2\alpha e(k)$. These two equations form the basis of the Widrow-Hoff (LMS) learning algorithm.

These results can be extended to the case of multiple neurons, and written in matrix form as

$$W(k+1) = W(k) + 2\alpha e(k)x^T(k)$$

$$b(k+1) = b(k) + 2\alpha e(k)$$

Here the error e and the bias b are vectors and α is a learning rate. 2α is often replaced by μ, the so-called step size of the algorithm. Thus,

$$W(k+1) = W(k) + \mu x(k)e^*(k)$$

If the step size μ is large, learning occurs quickly, but if it is too large it may lead to instability and errors may even increase. To ensure stable learning, the learning rate must be less than the reciprocal of the largest eigenvalue of the correlation matrix $x^T x$ of the input vectors.

Chapter 8

AODV enhanced by Smart Antennas

In the recent years, ad-hoc networking has driven much attention from the wireless research community and industry. Ad-hoc networks form when stations with similar architecture come into close proximity and start to communicate spontaneously. Therefore, ad-hoc networks must build their own infrastructure in a dynamic and distributed way, without any centralized coordination. Ad-hoc networks are often used for military systems, disaster area networks and conference networks. As wireless communication is more and more embedded into different devices, the role of ad-hoc networks is expected to expand. This larger use of ad-hoc networks also anticipates the development and enhancement of ad-hoc routing protocols, like for example the AODV protocol.

Also in recent years, AAAs have been increasingly tested for use in mobile applications. However, most of the commercial wireless communication systems are omni-directional and multiple antenna systems have only very slowly found their way into commercial applications. This is due to their cost and rather poor support from legacy air interfaces. But in the past few years, the cost for multiple antenna systems has been decreasing steadily and it seems that AAAs will eventually find their place in future ad-hoc networks. The potential benefits of using such AAAs in ad-hoc networks include increased network capacity, enhanced service quality and improved low power mode operation. Thus, they bring many advantages to ad-hoc networks and its routing protocols.

In this chapter, the topic of the project will be reminded and compared to a related work, the method and structure of the project will be illustrated and the state of the project will be described.

8.1 Topic of the Project

It may be useful to review the main objectives of the project. There are two main objectives, as follows:

- *Developing Technologies* – The implementation of the different network technologies introduced in this document, namely the wireless ad-hoc network and the adaptive array antenna;
- *Showing the Improvement* – Moreover, it is aimed to show that the adaptive array antenna improves the performance of wireless ad-hoc protocols, such as AODV, thanks to the higher gain of the antenna for example.

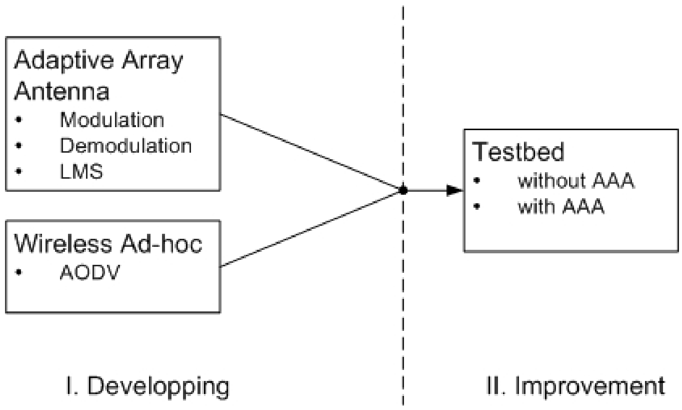


Figure 8.1: Topic of the project

8.2 Methodology and Structure

After introducing the main objectives of the project, the methodology and structure of the project shall be generally described. Further details may be gathered from the implementation code of the project, which can be entirely found in [11].

8.2.1 Development Methodology

The project was established by using the *Java programming language*, because of the multiple advantages it features. Java as an object oriented language is very effective and efficient, even if in some cases various problems were encountered, as for example for mathematical calculations.

The major advantage of the Java Technology may be its portability, so the whole developed code should be easily executable on various operating systems. The only prerequisite is to have a Java Runtime Environment installed on the system. Note that this project was implemented with the version J2SE 1.5.0 of Java.

Furthermore, to simplify the implementation, an editor tool for Java, namely the *Eclipse* toolset for development, has been used.

Java Technology

The Java technology readily harnesses the power of the network because it is both a programming language and a selection of specialized platforms. As such, it standardizes the development and deployment of the kind of secure, portable, reliable, and scalable applications required by the networked economy. Because the Internet and World Wide Web play a major role in new business development, consistent and widely supported standards are critical to growth and success [9].

- *Java Programming Language*

  The Java programming language lets you write powerful, enterprise-worthy programs that run in the browser, from the desktop, on a server, or on a consumer device. Java programs are run on – interpreted by – another program called the Java Virtual Machine—Java VM. Rather than running directly on the native operating system, the program is interpreted by the Java VM for the native operating system. This means that any computer system with the Java VM installed can run a Java program regardless of the computer system on which the application was originally developed.

- *Java Platform*

  The Java platform is a software-only platform that runs on top of other hardware-based platforms. Because hardware-based platforms vary in their storage, memory, network connection, and computing power capabilities, specialized Java platforms are available to address applications development for and deployment to those different environments.

  Java technology has grown to include the portfolio of specialized platforms. Each platform is based on a Java VM that has been ported to the target hardware environment. This means, for example, in the case of Desktop Java, desktop applications written in the Java programming language can run on any Java VM-enabled desktop without modification.

Eclipse – Universal Toolset for Development

The Eclipse Platform is designed for building integrated development environments (IDEs) that can be used to create applications as diverse as web sites, embedded Java programs, C++ programs, and Enterprise JavaBeans.

With Eclipse installed on the system it is very easy to modify and execute Java Classes as it provides many additional functions to improve the implementation, like the automatic search for syntax errors and the fact that classes can directly be executed as an application within the Eclipse editor [15].

8.2.2 General Structure

In this section, the general structure of the project will be described for a better understanding of the operation and functioning of the code.

First, a closer look on the Figure 8.2 should give an overview of the different elements needed within the development. Then each of the elements will be shortly explained.

Adaptive Array Antenna Structure

In a first phase of development, the elements of the adaptive array antenna should be implemented. All the elements needed are described in the following points.

- *Complex Number – Signals*

  Fundamental for the work on antenna technologies is the use of complex numbers, as every signal transmitted will be represented by a complex number. So it would be necessary for further work to implement the following operations: addition, subtraction, multiplication and conjugation of complex numbers.

- *Modulate Signal*

  For the treatment of signals on the physical layer. The first element to implement would be the modulation of the signal.

  In this project, the BPSK method for modulation of signals, containing the application of the well known Euler's theorem for complex numbers, has been chosen, because of its simplicity. This method is divided in two main steps:

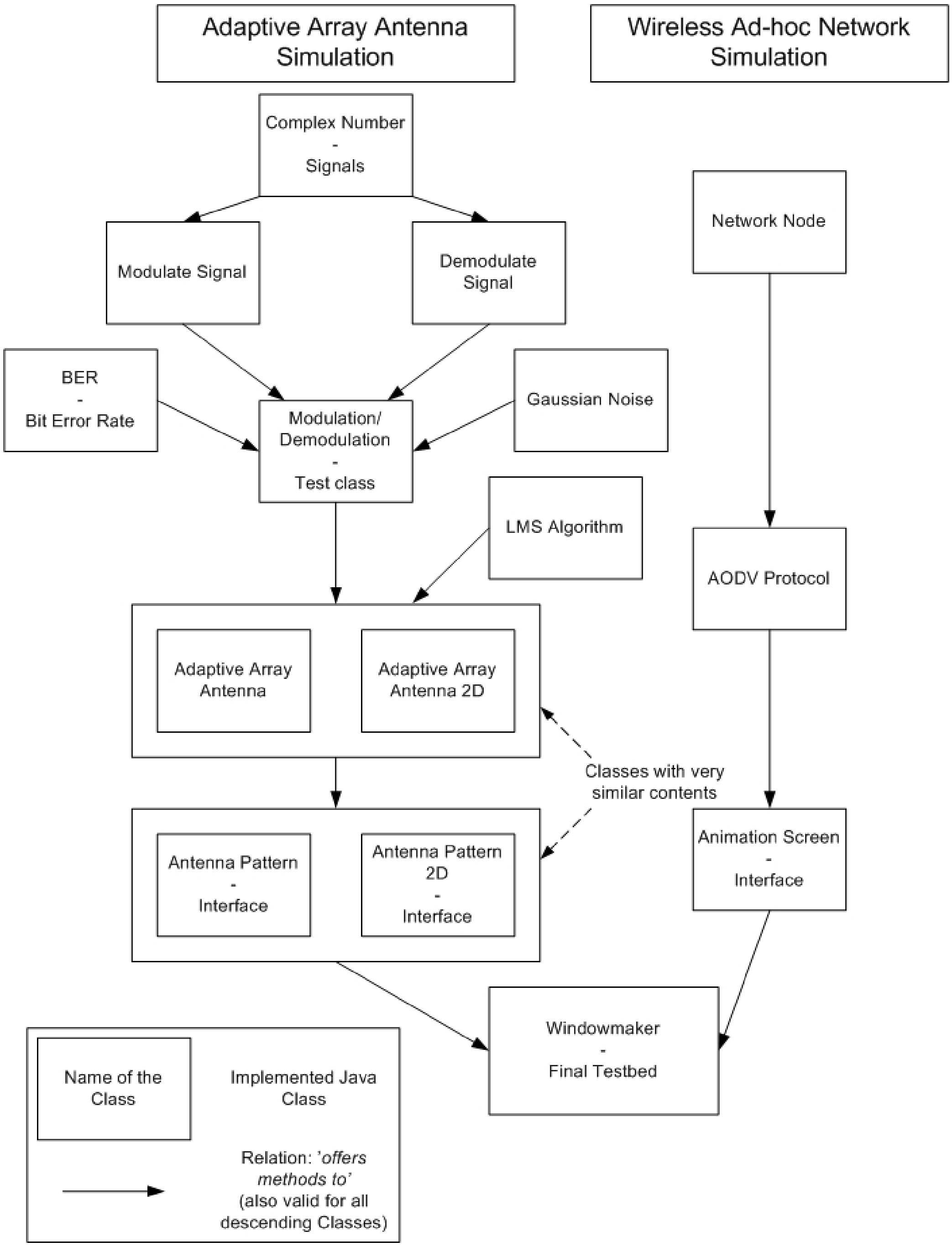


Figure 8.2: General structure of the project

- The first is to convert the original bit sequence into a signal by phasing it. This is a very simple step, to know the multiplication of each bit by π.
- The second step consists in the application of the Euler's theorem:

$$e^{ix} = \cos x + i \sin x$$

And the result, which is in fact a complex number, can be treated as a carrier signal and sent out to the destination.

- *Demodulate Signal*

  Once the carrier wave has arrived at the destination, it is necessary to demodulate the signal, in order to recover the initial bit sequence. This is performed by applying the steps of the BPSK method in reversed order.

  The problem of sending bit sequences is that during propagation and reception of the data signal, noises may be added to the original signal and thus modify the bit sequence. There are two ways that noises may get added, either by the channel or by the antenna itself. So the receiver of the signal has to recover the original error-free bit sequence out of a noisy one. Therefore, there are many different methods to do so. However, for the project the easiest one was chosen, which is the quantization of the signal.

  The demodulation including the quantization method is rather simple in this case. It suffices to take the incoming signal's bit sequence and either put the bit on 0 if the result is higher than 0, or put the bit on 1, if it's smaller than 0.

- *Gaussian Noise*

  To simulate the noise, which can be added while transmission or by the antenna of the signal through the medium, another element should be implemented.

  Within this project, the Gaussian noise is used to modify the incoming signal.

- *BER - Bit Error Rate*

  After the completion of the modulation and demodulation, the *Bit Error Rate* (BER), which in fact is a comparison of the initial bit sequence with the output bit sequence, had to be calculated. Thus the

BER indicates the amount of errors within the output sequence, due to noise addition or due to the channel.

To calculate the BER, it would be enough to check if the bits of the two sequences, the original and the received one, are the same. If they are not, the error counter will be incremented for each error found. At the end of the comparison the counter is divided by the length of the sequence and so the result is a number between 0 and 1, where 0 correspond to 'no error was found' and 1 to 'a completely wrong output sequence'.

- *Modulation/Demodulation – Test class*

  This element is an executable class to test the operation of the modulation, demodulation and the calculation of the BER. It would simply be used to simulate the transmission of a signal over the medium. The final output of this executable element should be the BER.

- *LMS Algorithm*

  The next element of the project is the implementation of the LMS algorithm, which helps to complete the elements of an AAA.

  The result of the application of the LMS algorithm in an AAA is represented in the Figure 8.3. It shows the the evolution of the gain, starting from the normal isotropic gain, which is the same in all directions, to the adapted gain produced by the execution of the LMS algorithm.

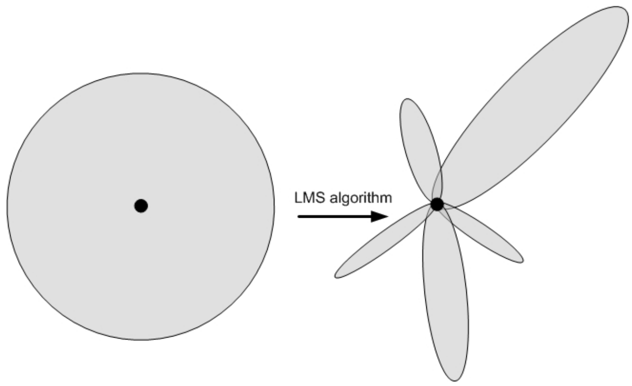


Figure 8.3: Application of the LMS algorithm

The LMS algorithm consists of repeated iterations of the three following formulas:

1. $y = W^H[k]x[k]$

2. $e^* = r - y$
3. $W[k+1] = W[k] + \mu x[k] e^*[k]$

The initial value of $k = 0$, of $y = 0$ and of $w = [1, 0, 0, ..., 0]^T$. x represents the incoming signal, r is the original signal and μ is called the step size.

The iteration is repeated exactly n times, where n is the length of the bit sequence.

- *Adaptive Array Antenna*

  After finishing the LMS algorithm, it should finally be possible to simulate the AAA correctly.

  However, the behavior of the antenna can now be completed by some more calculations. To simulate the reception of a signal, it was needed to calculate the steering vector of the antenna, then get the noise added by the antenna and finally calculate the received signal.

  The steering vector of an AAA is the vector, which indicates under which angle the incoming signal impinges each of the element antennas and is therefore needed to decide the phase of the signal. To calculate the steering vector, it is sufficient to apply the following formula:

$$a(\theta) = \begin{bmatrix} e^{j\phi_0} \\ e^{j\phi_1} \\ \vdots \\ e^{j\phi_{N-1}} \end{bmatrix} = \begin{bmatrix} 1 \\ e^{-j\frac{2\pi d}{\lambda}\sin\theta} \\ \vdots \\ e^{-j(N-1)\frac{2\pi d}{\lambda}\sin\theta} \end{bmatrix}$$

  where d is the distance between each elemental antenna, θ the angle of the incoming signal, and $\lambda = \frac{3\times10^8}{f} \approx 0.15$ m, generally a frequency f of 2 GHz is used.

  The noise added is just another Gaussian noise and to calculate the received signal, the following formula has been used:

$$x(t) = a(\theta)s(t) + n(t)$$

  where a is the steering vector, s the original signal vector and n the Gaussian noise vector.

  With these calculations, it is possible to display the antenna pattern of the AAA. The differences between the one-dimensional (θ) and the two-dimensional (θ, ϕ) pattern are mainly the steering vector used by the

AAA. For the two-dimensional pattern, the vector was not calculated in one dimension but two, but to simplify the task of representing the antenna pattern, one dimension was supposed to be constant, namely the θ-value to 90°. Therefore, the representation of the two-dimensional pattern would be in a circular form and only the calculation of the steering vector had to be modified.

- *Antenna Pattern – Interface*

  Now that the antenna should operate in a correct way, a user interface would be necessary, to draw the antenna pattern into a window. Fundamental for the simulation would be that the user can easily modify the parameters and therefore, the *swing*-package that Java proposes to create interfaces was chosen. Also the evolution of the pattern should be displayed in the window without any flickering on the screen and therefore a mechanism called double buffering was implemented (which afterward was used in all animations) to avoid such display errors.

  Furthermore, the two-dimensional pattern of the antenna should also be developed. This step was necessary because the antenna pattern should be included into the user interface for the AODV protocol, to combine the wireless ad-hoc environment and the AAA needed to complete the second main objective of the project.

Example of Execution

- *One-dimensional Interface*

  The interface for the one-dimensional pattern, shown in Figure 8.4, is the first executable interface developed in this project. By executing the Java class *AntennaPattern*, a simple window opens. The interface includes different parameter fields:

  - μ: the step size
  - *Elem. Ant.*: the number of element antennas within the AAA
  - *Length*: the length in bits of the sequence to be transmitted
  - *SNR*: the signal-to-noise ratio, the ratio of the amplitude of a desired data signal to the amplitude of noise. SNR is typically expressed logarithmically in decibels (dB).
  - *Alpha*: the α-value of the antenna, which is in fact the spacing between two element antennas divided by λ

– *Theta*: the angle in degrees of the incoming signal, should be between -90° and 90°

– *Theta interf.*: the angle in degrees of an interfering signal, should also be between -90° and 90°

Each of these parameters can be modified by typing a value in the corresponding parameter field. However, this simulation of the AAA only supports the interference of one undesired signal.

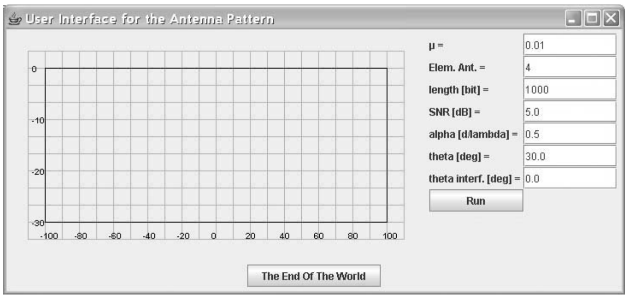


Figure 8.4: Interface for the one-dimensional pattern

The animation is started by a click on the Run-button; the program takes the values of the parameters and executes the simulation of the antenna. To stop the program and close the window, the user can simply click on the End-button or the X in the upper right of the window.

Figure 8.5 shows an example of execution. The following values were used:

– μ: 0.01

– *Elem. Ant.*: 4

– *Length*: 1000

– *SNR*: 5.0

– *Alpha*: 0.5

– *Theta*: 30.0

– *Theta interf.*: 0.0

• *Two-dimensional Interface*

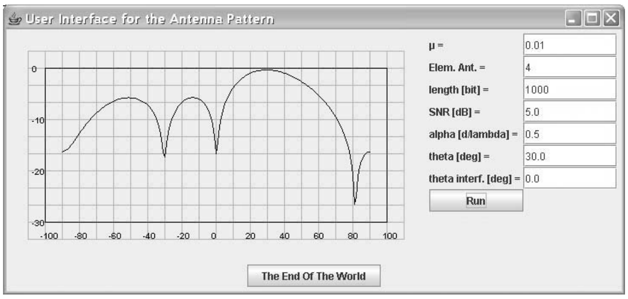


Figure 8.5: Example of execution result

The interface for the two-dimensional pattern, shown in Fugure 8.6, is the second executable interface developed in this project. By executing the Java class *AntennaPattern2D*, a simple window opens. The interface includes different parameter fields:

- μ: the step size
- *Elem. Ant.*: the number of elemental antennas within the AAA
- *Length*: the length in bits of the sequence to be transmitted
- *SNR*: the signal-to-noise ratio, the ratio of the amplitude of a desired data signal to the amplitude of noise. SNR is typically expressed logarithmically in decibels (dB).
- *Phi*: the angle in degrees of the incoming signal, should be between 0° and 360°
- *Phi interf.*: the angle in degrees of an interfering signal, should also be between 0° and 360°

Each of these parameters can be modified by typing a value in the corresponding parameter field. However, this simulation of the AAA only supports the interference of one undesired signal.

The animation is started by a click on the Run-button; the program takes the values of the parameters and executes the simulation of the antenna. To stop the program and close the window, the user can simply click on the End-button or the X in the upper right of the window.

Figure 8.7 shows an example of execution. The following values were used:

- μ: 0.01

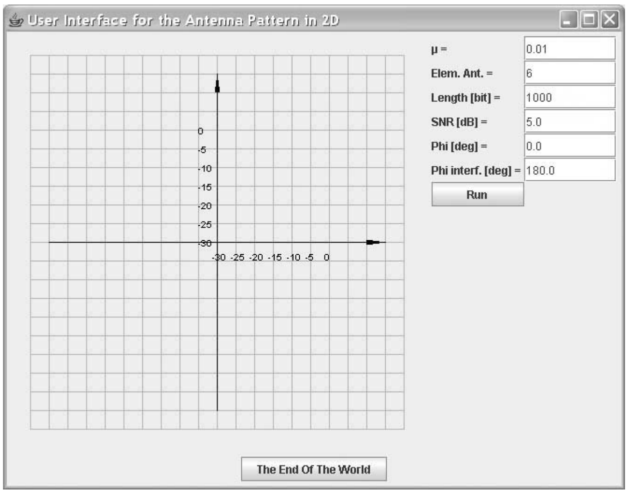


Figure 8.6: Interface of the two-dimensional pattern

- *Elem. Ant.*: 6
- *Length*: 1000
- *SNR*: 5.0
- *Phi*: 0.0
- *Phi interf.*: 180.0

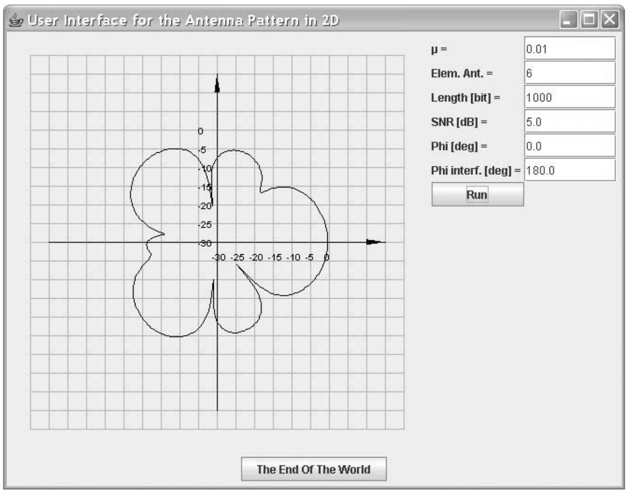


Figure 8.7: Example of execution result

Wireless Ad-hoc Network Structure

In this second phase of the development, the elements of the wireless ad-hoc network environment should be implemented. All the elements needed are described in the following points.

- *Network Node*

  Before starting to develop the AODV protocol, a basic element had to be created, the network node. This element created to simulate a node in a wireless ad-hoc network has to operate as a router and thus, includes the routing table, and relies on the AODV protocol. The position of the node is also included for the graphical representation and for the calculation of the neighboring nodes.

  The routing table is a simplified version of an actual AODV routing table. It only contains the fields needed within this project, namely:

  - Number of the destination node of a route, which is also the ID of a node
  - The most recent DSN of the node
  - The next hop for the route to the destination
  - The remaining number of hops to the destination

  This routing table is continuously maintained during the execution of the AODV routing operations.

- *AODV Protocol*

  Finally, the data link layer protocol could be implemented. For several reasons the AODV protocol has been chosen.

  It has already been described in detail in Chapter 4. Now should be mentioned which simplifications have been made for the sake of the project.

  - In the simulation the nodes are not yet mobile or susceptible to failures. So it was not needed to implement the third message, namely the route error (RERR) message. Neither was it requested to implement the procedures of renewing the route.
  - The implementation is not working on a real network, but treats only nodes which are represented by a matrix structure in Java. Thus, the nodes are not independently active objects as they should be in a real network and therefore, the quest for a route request is not parallel, but recursive. AODV as a dynamic protocol is very fast but it was not possible to simulate this fact by using recursive programming only.
  - Due to the recursive aspect, the RREQ will travel the entire network, before going into the second phase of the route establishment. Normally, the RREQ would be sent by the destination node as soon as it is reached. This fact is very time costly.

The last two points need some clarification. In the implementation of the protocol, a matrix, called *connect*, is used to represent the topology of the network. The position (i, j) of the matrix, is either a 0, if nodes i and j are not connected, or 1 if nodes i and j are connected. Thus, while executing the protocol, the RREQ broadcast message scans the matrix recursively. Therefore, it is not possible to work with two nodes in the network at the same time (which should be possible in real networks, as every single node represents a single station). Moreover, the matrix has to be fully scanned before entering the RREP message phase, whereas in AODV, the second phase starts as soon as the destination node is reached.

A short example, presented in Figure 8.8, illustrates the working of our recursive implementation of AODV.

Assume we have the following matrix *connect*,

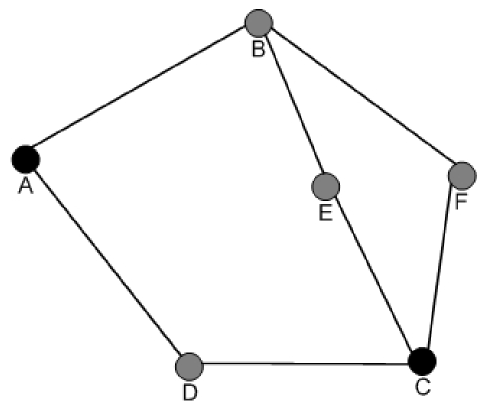


Figure 8.8: Example of AODV operation

	A	B	C	D	E	F
A	$-$	1	0	1	0	0
B	1	$-$	0	0	1	1
C	0	0	$-$	1	1	1
D	1	0	1	$-$	0	0
E	0	1	1	0	$-$	0
F	0	1	1	0	0	$-$

In the example, we would like to find a route from source node A to destination node C. Therefore, the execution of our AODV algorithm will lead us to the following communication routes:

$$A - B - E - C$$

$$A - B - F - C$$

$$A - D - C$$

By taking a closer look on the operation of our AODV implementation, the following table may be found:

Iteration	Route	Details
1	A	Start – next hops: B or D
2	A-B	Choice B, next hops: E or F
3	A-B-E	Choice E, next hop: C
4	A-B-E-C	First route is found
5	A-B-E	Go back to E, no next hop
6	A-B	Go back to B, next hop F
7	A-B-F	Choice F, next hop: C
8	A-B-F-C	Second route is found
9	A-B-F	Go back to F, no next hop
10	A-B	Go back to B, no next hop
11	A	Go back to A, next hop: D
12	A-D	Choice D, next hop C
13	A-D-C	Third and shortest route found
14	A-D	Go back to D, no next hop
15	A	Go back to A, no next hop – end

Thus, in our example, the algorithm chooses the route $A - D - C$, because of the lesser hops it has, compared to the other two routes.

This example shows how our implementation of the AODV protocol suffers from the simplifications listed above. Enhancing the working of the protocol and lifting the limitations could be the subject of future work.

- *Animation Screen – Interface*

  After having developed the AODV protocol, a user interface to display the route establishment of the AODV protocol should be developed. Two user-defined parameters should be included, namely the ID number of the source node and that of the destination node.

Examples of Execution

In this section some examples of execution of the AODV interface will be presented.

- *AODV Interface*

  By executing the Java class called *AnimationScreen*, a simple window opens. In the interface a random ad-hoc network is established, where every node is identified by its identification number (ID). Around each node, the range of the antenna will be displayed with a small animation to let the user see that the antenna is working. Furthermore, neighbor

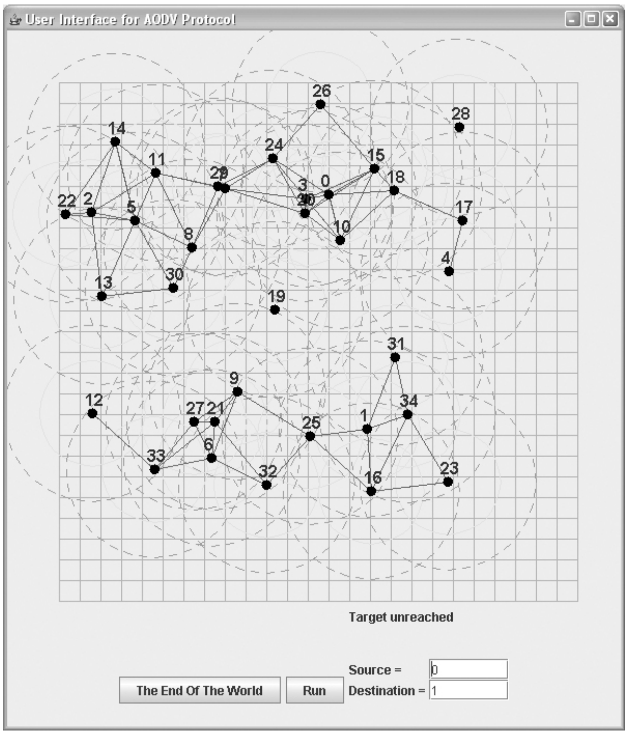


Figure 8.9: Starting screen of the AnimationScreen.class

nodes within the range of a node will be marked with a link between the neighbor and the node itself.

After entering the parameters, namely the identification numbers of the source and destination nodes, into the text fields, it suffices to click on a Run-button in the interface to execute the simulation. At all time, the user can stop the execution by simply clicking on the End- or on the X-button.

On the screen, the user can see how the protocol searches for the shortest route from the source node to the destination node.

There are two phases of execution as described below.

- *First Phase – RREQ message braodcast*

  The first phase is the RREQ phase, represented in Figure 8.10, where the source node searches a route to the destination. It starts with the source that broadcasts a RREQ messages to its neighbors. The neighbors then save the reverse route to the source node in their routing table and continue to send the RREQ messages to their neighbors and so on.

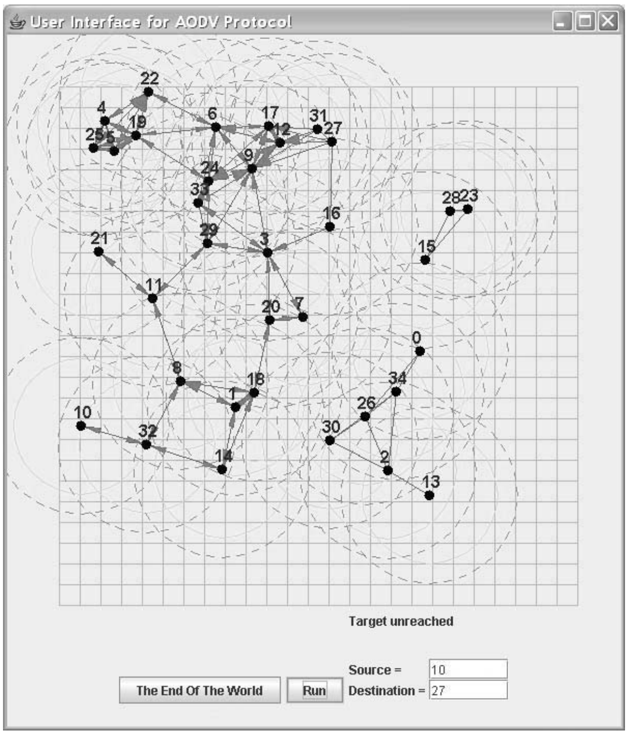


Figure 8.10: RREQ message broadcast

Once the whole network has been searched the protocol enters the second phase.

- *Second Phase – RREP message response*

  The second phase, the route reply phase, starts with the destination node who has received the RREQ messages responding with a route reply (RREP) message which is sent on the reverse route on the shortest way to the source node, saving this time the route to the destination node in the routing table of each node.

  Once the RREP message has arrived at the source node, the route is established and the interface shows the number of hops from the source node to destination node.

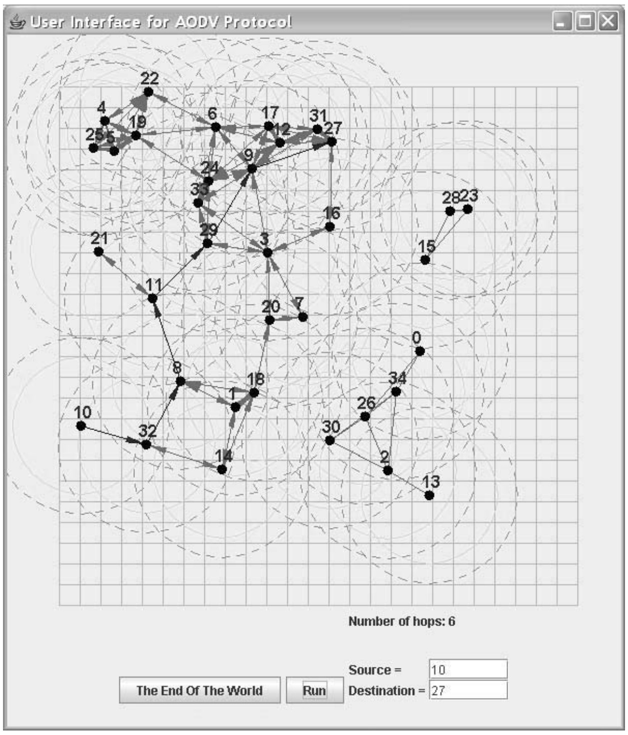


Figure 8.11: RREP message response

Final Testbed

The final testbed is the combination of the AAA and the ad-hoc network environment. With this element completed, the second objective, namely the testing and comparing of different configuration, could be easily started.

To clarify the possible enhancement by applying a smart antenna in a ad-hoc routing protocol like AODV, a short example scenario will be illustrated.

As seen in Figure 8.12, after applying the AODV protocol a first time (2), a route is traced from source node 1 to destination node 3. This route is in fact a multihop route making two hops to destination. By establishing this route, the AAA could apply its adaptive filter to point the main lobe towards node 2 (3), which represents the next hop on the route. Luckily, in this scenario the destination node 3 lies in the same direction as node 2 and moreover, it lies in the range of the main lobe. So, it could be imagined that after applying the AODV protocol a second time (3), the source node 1 could effectively reach the destination node 3 in only one hop, thanks to the new antenna pattern.

Finally, it is easy to figure out other examples of possible enhancements as smart antenna technology can increase the potential for spatial reuse and

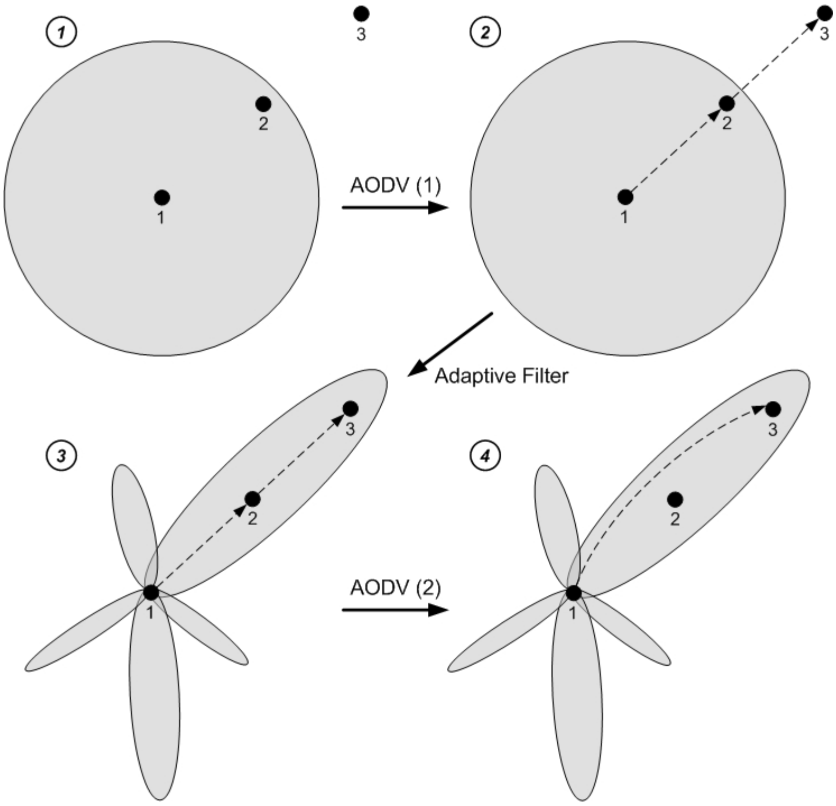


Figure 8.12: Possible enhancement of smart antennas in AODV routing

can provide longer transmission and reception ranges for the same amount of power. This could be translated into higher ad-hoc network capacity, improved connectivity, reduction of eavesdropping risk and suppression of unnecessary interference.

8.2.3 State of the Project

A short review of the elements, which have already been accomplished in the project:

- The adaptive array antenna and all of its elements
- Elements of the wireless ad-hoc mechanisms, namely the network nodes, the AODV protocol and its user interface

The element still to completed to finalize the second goal of the project is:

- The final testbed, which combines the AAA and the ad-hoc network environment

8.3 Related Work

As a reference to this project and to better understand the topic of this work, the article [3] should be mentioned shortly.

In this article, a complete solution for ad-hoc networks with directional antennas is proposed [3]. Thus, a clear relation to this project can be drawn. A method called 'Utilizing Directional Antennas for Ad-hoc Networks', short *UDAAN*, is introduced. UDAAN is an interacting suite for modular network- and MAC-layer mechanisms for adaptive control of steered or switched antenna systems in an ad-hoc network. It consist of several new mechanisms—a directional power-controlled MAC, neighbor discovery with beamforming, link characterization for directional antennas, proactive routing and forwarding. The article describes also the development of a real-life ad-hoc network testbed using UDAAN with switched directional antennas.

Following differences in both works can be pointed out:

	This Document	**Article 2005.018**
Antenna Technologies	Adaptive Array Antenna	Steered or switched antenna
Routing Protocol	AODV	HSLS
MAC protocol	CSMA/CA	CSMA/CA with directional MAC
Neighbor discovery	Implicit	Explicit

The article points out many advantages of smart antenna technologies in ad-hoc networks in both theoretical and practical ways. The basic ideas behind that work are the same as for this project. The main difference is that that work is completed, and the advantages already shown in a series of tests. Despite those results, the present project shall bring new knowledge about the topic, considering the differences listed in the table above.

Chapter 9

Conclusion

In this short chapter, the achievements and the work still to accomplish will be reviewed. The project is not yet entirely concluded and therefore, the topics for future works will also be recalled in this chapter.

First of all, to recall the elements already developed and operational:

- *Adaptive array antenna elements* – calculation of complex number, modulation and demodulation, Gaussian noise, BER, LMS algorithm, antenna pattern;
- *Wireless ad-hoc elements* – network nodes, AODV protocol, and its user interface

However, the following elements have not yet been developed due to a lack of time and thus, could be the object for future work:

- *Final testbed* – After the completion of the other two elements, this final object should be easy to install too. The goal is to implant the adaptive array antenna into the wireless ad-hoc environment and thus, obtain a functional network to use during the second phase of the project.

After completing these elements, the project can enter the second phase, to remember:

To prove or at least to test the assumption that the adaptive array antenna improves the performance of the wireless ad-hoc protocol AODV, by testing the general operation of the simulated system, by creating different network configurations and compare the performance of AODV with and without the presence of the antenna.

Moreover, there are several enhancements, which could complete or enhance the operation of the AODV protocol, to remind:

- In the simulation the nodes are not yet mobile or susceptible to failures. So, it was not needed to implement the third message, namely the route error (RERR) message, nor the procedures of renewing the route. This could be a very interesting feature, also for testing in combination with the adaptive array antenna.

- The implementation is not working on a real network, but treats only nodes, which are represented by a table structure in Java. Thus, the nodes are not independently active objects as they should be in a real network and therefore, the execution of a route request is not parallel, but iterative. AODV as a dynamic protocol is very fast, but it was not possible to simulate this fact only by using iterative programming. The tests in the second phase should be possible without this feature, but to have more realistic results it is fundamental.

- Due to this iterative aspect, the protocol also has to search the entire network, before going into the second phase of the route establishment. This fact is very time costly, and thus, will deliver unrealistic results during the tests. But as both configurations will use the same protocol, the improvement, if any, should be visible.

This concludes this document. For further informations about the project and the development, please refer to the Report of Work Experience [11], which includes detailed information about the development and also the entire code of the project.

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